THE UNIVERSITY OF ALBERTA

Quaternary sedimentation and stratigraphy of montane glacial deposits in parts of Jasper National Park, Canada

by

© VICTOR M. LEVSON

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Quaternary sedimentation and stratigraphy of montane glacial deposits in parts of Jasper National Park, Canada submitted by Victor M. Levson in partial fulfilment of the requirements for the degree of MASTER of SCIENCE.

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Stelck

Date ....April 23/86........

Abstract

Glacial diamictons described and sampled during regional stratigraphic studies in Jasper National Park, Alberta, Canada, were categorized using a facies approach. The classification scheme was based only on objective field criteria but it was designed to ultimately aid in genetic interpretations of the described deposits which are required for meaningful stratigraphic correlations. It is hoped that the till 'facies' described for the Jasper region will be applicable with modifications to other mountain areas, as well as provide a basis for the development of non-genetic classification schemes of glacial deposits in other environments.

Eight main diamicton types and six subtypes were recognized: 1) Massive diamicton (subtype 1a - with rare, steeply dipping sand and gravel lenses and layers; subtype 1b - with rare, plano-convex, sand and gravel lenses); 2) Massive diamicton with abundant striated, faceted and embedded clasts; 3) Banded diamicton; 4) Massive diamicton containing circular sand and gravel lenses; 5) Bouldery diamicton with numerous, highly disturbed, sand and gravel lenses and layers; 6) Massive to moderately stratified diamicton containing trough-shaped, sand and gravel lenses, (subtype 6a - dominantly diamicton with disrupted stratification in the sorted materials; subtype 6b - diamicton less dominant and contains abundant undisturbed lenses); 7) Coarse textured diamicton interbedded with sands and gravels (subtype 7a - matrix sandy; subtype 7b - matrix gravelly); 8) Massive diamicton interbedded with horizontally laminated silts and clays.

Environmental interpretations of the glacial diamictons are based on information presently available from process studies in modern glacial environments. The eight types can be grouped into four major genetic categories based on interpretations on the position of formation within a glacier: 1) basal tills (types 1 to 3); 2) englacial tills (type 4); 3) supraglacial tills (type 5); and 4) ice-marginal deposits (types 6 to 8). Till types of the first two genetic categories commonly are vertically and laterally gradational with one another. This basal / englacial sediment association occurs because types 1 to 4 apparently all formed in the basal debris-rich zone (although type 4 diamictons were entirely encased within ice at the time of formation). Contacts between till types 1 to 4 usually are conformable further suggesting a genetic relationship. Similarily, till types 5 to 8 form a supraglacial / ice-marginal sediment association since they usually occur together and grade laterally into one another. Contacts separating till types of the basal / englacial sediment association (types 1 to 4) from those of the supraglacial / ice-marginal sediment association (types 5 to 8) commonly are erosional.

The utility of the facies approach in solving stratigraphic problems was tested by the analysis of a complex sequence of glacial diamictons in the Portal Creek area. The genetic interpretations placed on the facies were validated by a general agreement between the expected and observed facies sequences, and also proved useful in solving stratigraphic problems.

Stratigraphic and provenance studies in the Portal Creek region reveal three major sediment packages of distinct provenance indicating that three separate glacial events may have occurred. However, an environmental analysis of the deposits shows that the oldest two groups of sediment probably were deposited during the same episode. Changes in till provenance are believed to be the result of fluctuations in the dominance of two confluent glaciers originating in different valleys. The facies analysis supports the stratigraphic evidence that the third sedimentary package was deposited in a distinct glacial episode at a significantly later time than the underlying deposits. Although stratigraphic correlations with dated sediments are tentative, both glacial events recorded in the Portal Creek stratigraphic record are presumed to be Late Wisconsinan in age.

Acknowledgments

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"Daddy when you finish your school program will you play with me?"
Yes Timmy, I'd love to.

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I. Introduction

This thesis was initiated as a stratigraphic study of Pleistocene sedimentary deposits in Jasper National Park. The park was chosen as a field area because the Quaternary stratigraphy of the region had never been investigated. Reconnaissance surficial mapping and stratigraphic studies were carried out during the summers of 1982 and 1983. During analysis of the regional level data it soon became apparent that traditional stratigraphic methods were not suitable for the correlation of glacial deposits in the region. The major reason for this is the complex dynamics of glacial sedimentation in the mountain environment. Numerous authors (Sharp, 1949; Boulton, 1970; Karczewski and Wisnniewski, 1976; Boulton and Eyles, 1979; Eyles, 1979; Lawson, 1979a, 1981b, 1982; Haldorsen, 1982) have observed the large changes in depositional environment that can occur over short vertical and horizontal distances in valley glaciers. In addition, recent advances in the rapidly evolving fields of glacial sedimentology and till facies analysis have had major implications on the stratigraphic interpretation of complex Quaternary sequences (e.g. Proudfoot, 1985). Consequently, the original stratigraphic emphasis of this study shifted towards an environmental analysis of the glacial deposits in the region.

This thesis is one of the first systematic facies analyses of ancient glacial sediments in the mountain environment. The sediment categories presented have not been previously described. Facies designations are based on readily observable field criteria and, consequently, they are of use in regional stratigraphic studies where large numbers of outcrops must be described in a short time. Tills originate in complex depositional environments and an understanding of their genesis aids greatly in stratigraphic research. Consequently, the criteria used to distinguish till types in this study, although objective in nature, were also selected to be relevant for genetic interpretations which would ultimately aid in deciphering the stratigraphy of the area. Environmental interpretations were made mainly by reference to recent sedimentary analogues and process studies on modern glaciers. The accuracy of the genetic interpretations was tested by comparison of expected and observed facies sequences. Finally, a case study of a stratigraphically complex area was made to test the utility of the environmental interpretations in solving stratigraphic problems, the ultimate objective of this research.

Descriptive approaches to the analysis of glacial deposits have not been developed in the past, mainly because of the commonly massive and homogenous nature of tills. The facies designations described here rely heavily on the presence of stratified materials which are often intimately associated with the tills. This reliance on associated stratified sediments in the classification system is justified, as interpretations on till genesis are often largely based on these sediments (e.g. Lawson, 1979a, 1981a).

Recent till facies studies have been concentrated in prairie areas (Porter, 1983; Proudfoot, 1985) and little work has been done in mountain regions. It is hoped that the till classification system developed here for glacial sediments in a mountainous region will be applicable with modifications to other mountain areas, as well as provide a basis for the development of non-genetic classifications of glacial deposits in other environments.

A. Objectives

The objectives of this thesis are:

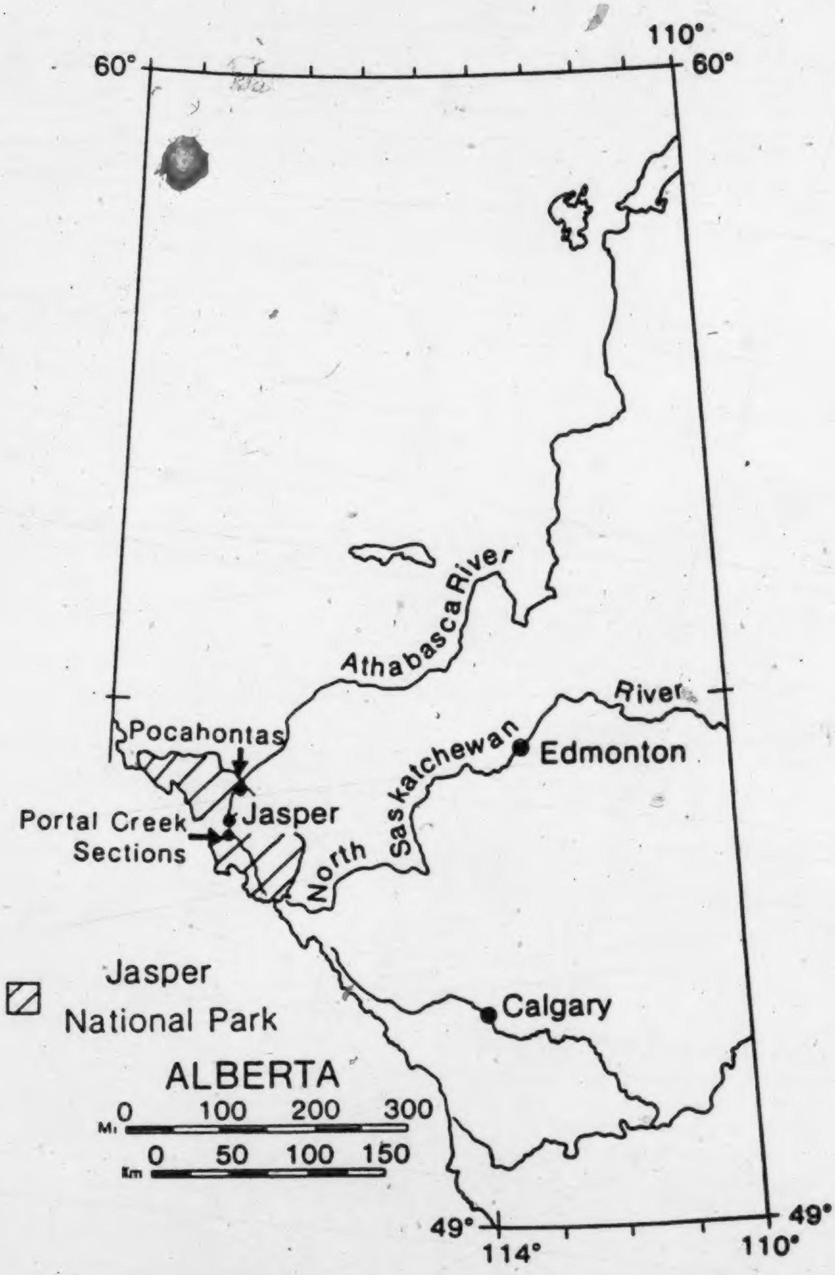
1. to describe the characteristics of glacial deposits observed during regional studies in the Jasper region;
2. to develop a till classification system based on objective field criteria that will ultimately be of use in genetic interpretations of the deposits and in regional stratigraphic studies;
3. to interpret the depositional environment of each till type by comparison with similar deposits in modern glacial environments; and
4. to test the usefulness of the classification system by the study of a stratigraphically complex area in the Jasper region and to determine the relevance of genetic interpretations of the classified deposits in solving specific stratigraphic problems.

B. Study Area

Location and Physical Setting

The study area is located in the Rocky Mountains of west-central Alberta and encompasses a large portion of Jasper National Park (Figure 1). The Continental Divide forms the western boundary of the study area. Jasper townsite (1058 m asl) lies

Figure 1: Location of study area.



approximately in the center of Jasper National Park (Figure 2). Relief in the region is high with mountain peaks commonly rising about 1500 m above valley bottoms. Mt. Robson, the highest peak in the Canadian Rockies (3954 m), occurs about 75 km west of Jasper. Studied sections occur mainly in the Athabasca, Miette, Whirlpool, Snake Indian, and Rocky river valleys, (Figure 2) where thick sequences of Quaternary sediments are present.

Climate

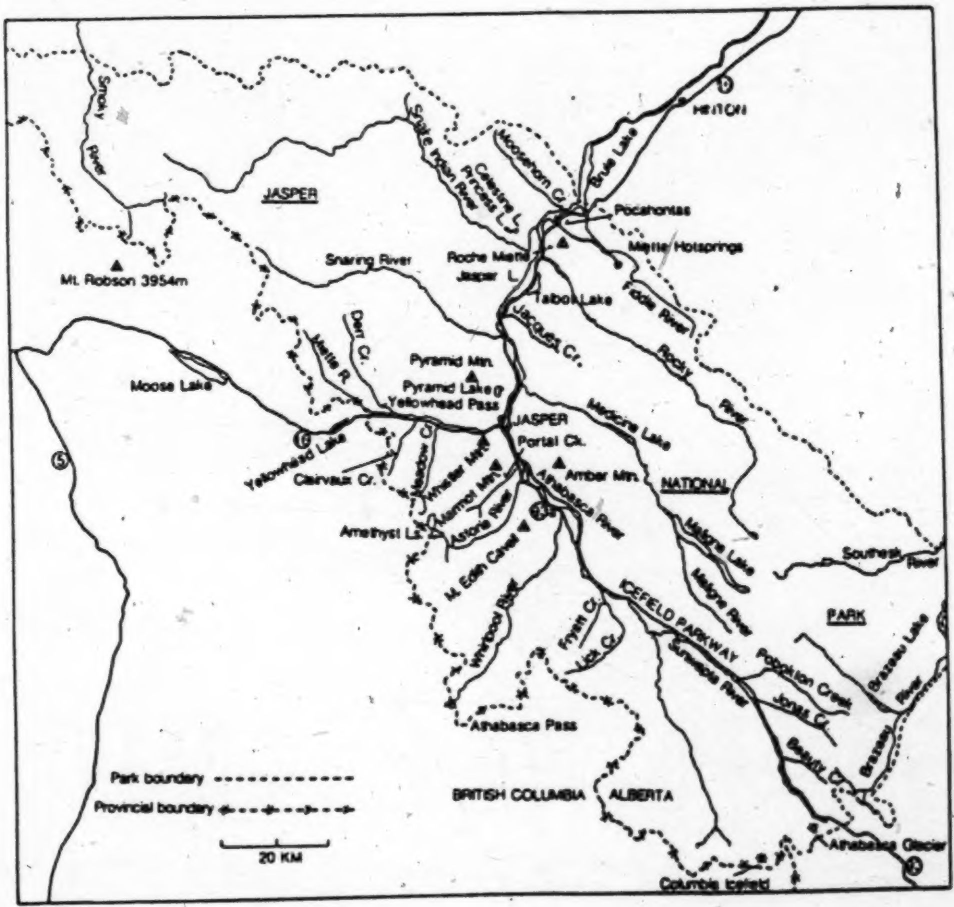
The mean annual, January, and July temperatures at Jasper townsite for the period 1941 to 1970 are 2.8°C, -12.2°C, and 15.2°C, respectively (Atmospheric Environment Services, 1971?). Total annual precipitation and snowfall are 401 mm and 1370 mm. Large variations in climate occur over short distances due to topographic control. Precipitation along the Continental Divide, for example, is much higher than in the valley bottoms and temperatures are lower, resulting in the development of extensive icefields.

Vegetation and Soils

Three main vegetation zones occur within the region reflecting climatic variations with elevation (Knapik and Coen, 1978). The montane zone in the valley bottoms and lower valley sides is characterized by xeric grasslands, lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menzeisii*), trembling aspen (*Populus tremuloides*), or white spruce (*Picea glauca*) ecotones. The subalpine zone occurs on higher elevations on valley sides and is characterized by subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*) and alpine larch (*Larix lyallii*). Treeline lies at about 2200 m on south facing slopes and 2000 m on north facing slopes. Various heather, willow, sedge, grass and dryas species are common in the alpine zone (Knapik and Coen, 1978).

Soils in large valleys such as the Athabasca are dominantly of the Luvisolic and Brunisolic orders with Gleysols frequently occurring along floodplains. With increasing elevation, there is a gradual transition from Luvisolic soils below about 1500 m to mainly Podzolic soils above. Regosols dominate on steep, unstable, slopes and, as such, they are a significant soil type in the study region (Knapik and Coen, 1978). Soil and vegetation maps of the area have been provided by the Jasper Biophysical Inventory (Holland and

Figure 2: Place names in study area.



Coen, 1982).

Physiography and Bedrock Geology

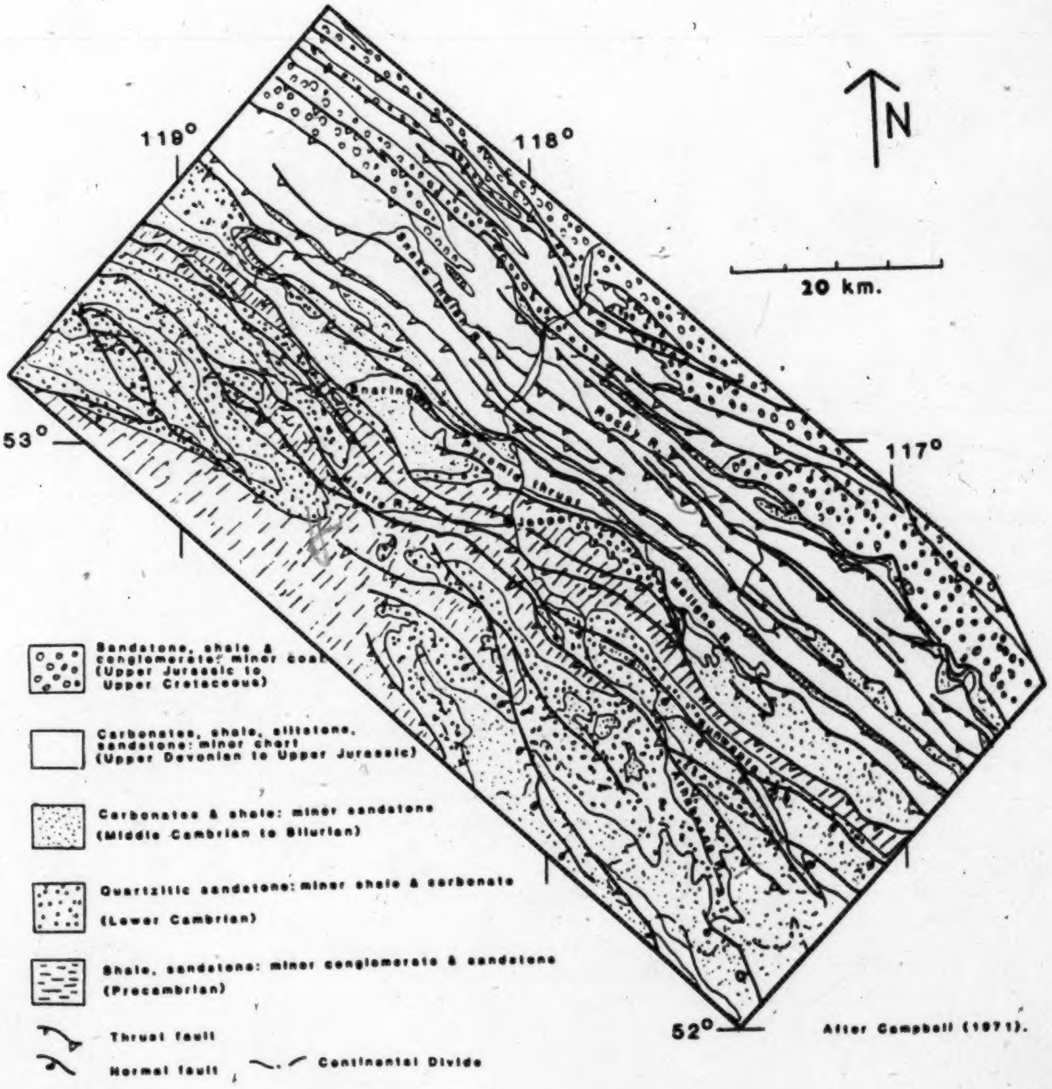
The geology of the Jasper region was first investigated around the turn of the century (Hector, 1863; McConnell, 1887; McEvoy, 1901; Rutherford, 1925; and Kindle, 1929). Later researchers worked mainly in the Sunwapta Pass area (Allan, 1938; Severson, 1950; and Hughes, 1955) and in the Foothills and easternmost Front Ranges (MacKay, 1943; Lang, 1947; and O'Brian, 1960). Detailed bedrock maps of the Jasper region were not published until the 1960's and later (Charlesworth et. al., 1967; Mountjoy, 1960, 1961, 1962, 1963, 1964; Mountjoy and Price, 1984 and 1985) and still are not available for all of the park. All of Jasper Park, however, has been mapped at a small scale (Price and Mountjoy, 1970; Campbell, 1971; and Green, 1972).

The study area lies entirely within the Main and Front Ranges of the Rocky Mountains Physiographic Region (Bostock, 1970). The Front and Main Ranges subprovinces are separated by the Pyramid Thrust in the south and the Snake Indian Thrust in the north (Mountjoy, 1981). The Front Ranges are comprised of a series of about 6 thrust sheets which have moderate to steep southwesterly dips. They are composed mainly of carbonates and shales from Upper Cambrian to Jurassic in age (Figure 3). Steep cliffs form on the northeast edge of the thrust blocks and more gentle slopes occur along the more gently dipping bedding planes. The northwesterly structural trend of the Front Ranges is emphasized by the development of valleys along relatively weak Mesozoic shales and sandstones which are separated by linear ranges of resistant Palaeozoic carbonate (Price and Mountjoy, 1970).

Within the study area, the Main Ranges subprovince consists of thick, relatively flat lying, or gently dipping, thrust blocks with broad folds and southwesterly dipping normal (gravity) faults (Price and Mountjoy, 1970). They are mainly composed of distinctly bedded carbonates, quartzose sandstones, and shales of Cambrian and PreCambrian age. Valleys have been carved mainly in the more intensely folded shales and sandstones of the PreCambrian Miette Group (Figure 3).

The northwest-southeast structural trend of the Rocky Mountains, has imposed a strong control on the orientation of river valleys, particularly in the Front Ranges. In the

Figure 3: Bedrock Geology of Study Region


119°
118°
117°
53°
52°
N
20 km.
Snake Indian R.
Snaring R.
Rocky R.
Pyramid thrust
Miette R.
Maligne R.
Sandstone, shale & conglomerate: minor coal (Upper Jurassic to Upper Cretaceous)
Carbonates, shale, siltstone, sandstone: minor chert (Upper Devonian to Upper Jurassic)
Carbonates & shale: minor sandstone (Middle Cambrian to Silurian)
Quartzitic sandstone: minor shale & carbonate (Lower Cambrian)
Shale, sandstone: minor conglomerate & sandstone (Precambrian)
Thrust fault
Normal fault
Continental Divide

After Campbell (1971).

Main Ranges, the relatively flat lying strata and broad folding has resulted in less structural control and many rivers flow from the area of the Continental Divide to the northeast. The Miette River valley is the most prominent of these and forms a major transportation corridor which crosses the Continental Divide at Yellowhead pass (Figure 2).

The main structural culmination in the Alberta segment of the Rocky Mountains occurs across the whole of the Main Ranges in the Jasper-Yellowhead Pass region and corresponds with the area of extensive exposures of the PreCambrian Miette Group (Price and Mountjoy, 1970). Most Main Range mountains, particularly those along the Continental Divide, are over 3000 m. Due to their high elevation, they are commonly ice covered and form rugged castellated peaks with well developed cirques and other glacial landforms. In contrast, peaks in the Front Ranges are mainly 2000 to 3000 m in elevation and support only one major icefield in Jasper Park (Brazeau Icefield). Due to this decreased glacial activity, as well as the pronounced structural control, glacially eroded features are poorly developed in the Front Ranges.

The geologic structure, stratigraphy, and tectonic evolution of the Rocky Mountains have been discussed by numerous authors in recent years. Summaries are provided by Price and Mountjoy (1970), Wheeler (1970), Wheeler et.al. (1972), Aitken and MacQueen (1976), Campbell et. al. (1976), Simony and Charlesworth (1976), Monger and Price (1979), and Price (1981).

C. Previous Work

Surficial Geology

No detailed analysis of surficial sediments of Pleistocene age had been carried out in Jasper National Park prior to this study. Previous research concentrated mainly on Holocene deposits and climatic change (Heusser, 1956; Bowyer-Beaudoin, 1977 and 1984; Kershaw, 1977; Luckman, 1977; Bednarski, 1979; Luckman and Osborn, 1979; Holland, 1980; Kearney, 1981; and Kearney and Luckman, 1981, 1983a, 1983b) and on the geomorphology and Neoglacial deposits of the Athabasaca Glacier region (Jennings, 1951; Ommanney, 1976; Mills, 1977a, 1977b; and Baranowski and Henock, 1978). The general geology, geomorphology and hydrology of the Maligne Valley region have been

5

described by Roed (1964), Brown (1970), Luckman (1973), and Mountjoy (1974).

Mapping of the Quaternary sediments in Jasper National Park has been carried out by Reimchen (1976) and Holland and Coen (1982). The hydrology of the southern part of the study area was reported on by Barnes (1978).

Glacial History

Roed (1975) studied the Quaternary Geology of the Edson - Hinton area, east of the study region. He found evidence for three glacial advances originating in the Jasper area. The oldest and strongest advance was the Marlboro, which flowed out of the Athabasca valley and coalesced with eastern ice in the vicinity of Edson (Figure 1) and was deflected to the southeast, parallel to the mountain front. Roed (1975) suggested that the Marlboro glacier transported the quartzite erratics of the Foothills erratics train described by Stalker (1956). The Athabasca Valley erratics train, consisting of low to medium grade metamorphic rocks (mainly talcose, garnet, and quartz-biotite schists), was also transported by the Marlboro glacier (Roed et. al., 1967). The source of these metamorphic rocks is probably in the Monashee Mountains or Premier Range of British Columbia. Consequently, the Marlboro glacier probably originated, at least in part, west of the Rocky Mountain Trench and flowed across the Continental Divide into Jasper National Park (Roed et. al., 1967). This is supported by the glaciated 'U-shape' of Yellowhead Pass and other passes along the Continental Divide west of Jasper.

The second glacial event recorded by Roed (1975) was the Obed advance which may merely have been a readvance of the Marlboro. When the Marlboro glacier had retreated to the Brule Lake area (Figure 2) it was subsequently incorporated by the Obed glacier which formed an extensive piedmont lobe at the mountain front. The youngest advance in the area (Drystone Creek) was short lived and restricted to higher elevations in the Front Ranges. Roed (1975) also found some evidence for a possible 'early' Cordilleran advance. The details of its history are obscure but it possibly flowed beyond the mountain front and met with an early Laurentide glacier. Although none of the advances were dated, Roed suggested that the Marlboro, Obed and Drystone Creek advances were Late Wisconsinan in age. More recently, the Marlboro advance has been considered to be Early Wisconsinan in age, although dating control is still lacking (Rutter, 1984).

Late Wisconsinan glaciers in the Jasper region had receded to near their present limits prior to about 10,000 years B.P. (Luckman and Osborn, 1979). A minor advance (Crowfoot) extending about one to two kilometers beyond present glacier margins probably occurred between 8,500-9,200 or 9,700-12,000 years B.P. (Kearney and Luckman, 1981).

D. Definitions

The terms "diamicton" and "till", as used in this thesis, follow the definitions given by Dreimanis (1982a).

Diamicton is defined as

> "any non-sorted or poorly sorted sediment that contains a wide range of particle sizes"

(Dreimanis, 1982a, p 15). By this definition diamictons may be matrix or clast supported although the former tends to dominate in poorly sorted and unsorted glacial deposits. Diamicton is a non-genetic term. It should be noted that poorly sorted gravels of fluvial origin are, by definition, diamictons while moderately sorted deposits (even of glacial origin) are not. The sorting scale used here is that of Folk (1980).

Till is defined as

> "a sediment that has been transported and deposited by or from glacial ice, with little or no sorting by water"

(Dreimanis, 1982a, page 21). The definition includes glacial debris deposited by sub-aerial or sub-aquatic mass movements off glacial ice. Such deposits have frequently been referred to as flow tills (eg. Boulton, 1968, Dreimanis, 1982a) and more recently as secondary tills (Boulton and Deynoux, 1981) or allo-tills (Dreimanis, 1982a).

However, some authors, particularly those working in modern glacial environments, do not consider secondary or resedimented glacial deposits as tills. Lawson (1981a, page 78) for example, defines till as

> "sediment deposited directly from glacier ice which has not undergone subsequent disaggregation and resedimentation".

This more restricted definition of till is not used here for two reasons:

1. The presence of glacial sediment in an area indicates the proximity of glacial ice at

one time, whether or not subsequent resedimentation occurred. Referring to debris that has flowed off glacial ice as a "sediment flow" rather than a "flow till" does not identify its glacial origin. Even though the glacial sediments may have developed new non-glacial properties, it is important for climatostratigraphic reasons to distinguish glacial and non-glacial deposits.

2. Tills deposited directly by glacier ice commonly grade into resedimented deposits and often they are indistinguishable even in the modern environment (Dreimanis, 1982a; Lawson, 1979a).

The use of a broader definition of till than that used by Lawson (1981a) does not prohibit the distinction of grounded ice and proglacial deposits, but merely allows for the identification of glacial deposits as such. The former distinction is critical for stratigraphic interpretations. Although it is not always possible to distinguish flow tills from non-glacial sediment flows a glacial sediment source can usually be recognized by the properties of individual clasts (e.g. erratic lithologies or striations). However, the possibility of remobilizing previously deposited till during non-glacial times must also be considered. Such deposits may often be recognized since they usually conform to the regional slope and they are mainly confined to the valley side. However, diagnostic criteria are not always present and the genetic interpretations placed on many deposits are subject to revision. For this reason, the term "diamicton" was used in the field and the term "till" is used only in an interpretive sense.

Glacial diamictons that have lenses, pods or other inclusions of sorted material may be referred to as tills provided that diamicton dominates throughout the unit (Dreimanis, 1982a). Thin diamictons of glacial origin may also be called tills even though they are interbedded with sorted and stratified materials but the entire sequence of such deposits should be referred to as a 'till complex' (Boulton and Eyles, 1979).

Flow till is defined here as

"till deposited by any mass movement of debris on or from glacial ice"

(Dreimanis, 1982a, page 18). Such glacially induced mass movements may occur by flowing, sliding, spalling, slumping or dropping (Lawson, 1979a; Dreimanis, 1982a). In addition, they may occur on the surface of a glacier, along the ice margin, or in subglacial and englacial cavities (Dreimanis, 1982a). Consequently, flow tills may have a wide variety of genetic origins in a sedimentologic sense and a more generalized term is needed when a specific glacial origin can not be positively confirmed. The term "debris flow" is used for this purpose. Adjectives used with the terms flow till or debris flow give information as to the position (e.g. subglacial or ice-marginal) or type (e.g. subaquatic) of flow.

Lodgement till is defined as

> "till deposited from the base of a dynamically active glacier by pressure melting and or other mechanical processes"

(Dreimanis, 1982a, page 24). Boulton (1971) also describes material released by melting of debris rich ice stranded beneath a moving glacier as lodgement till but this definition is considered too broad for use here as it overlaps with the definition of meltout till given below.

Meltout tills are

> "tills formed by the melting of debris rich ice that is neither sliding nor deforming internally in the zone of formation"

(Shaw, 1982, page 1549). The adjective "basal" when applied to meltout tills is meant to imply the source of the till within the ice not the location of melting (ie. melting from the top of the glacier as opposed to melting from the base) (Haldorsen, 1982). Many of the properties of the basal zone ice and debris are preserved during the formation of meltout till since the *in situ* melting occurs gradually and under confining overburden conditions which inhibit deformation (Lawson, 1979a, 1981a). *Supraglacial, englacial, subglacial (or basal)* and *ice-marginal* are generalized genetic terms which refer to the location of till *formation* not the depositional process as is the case for the specific till varieties defined above. In this context it is important to distinguish till *"formation"* from till *"deposition"*. Shaw (1982) pointed out that tills are *"formed"* when the individual particles within the till are largely in contact, even though they may overlie a substantial thickness of ice. Till *deposition* does not occur until all the underlying ice is removed (Shaw, 1982). The formation of englacial tills is not restricted to central positions within a glacier. They may form in basal positions provided that they are entirely encased in ice at the time of formation.

II. Methodology

A. Introduction

Detailed observations of the glacial deposits in the Jasper region were made in the summers of 1982 and 1983, particularily in stratigraphically complex areas. Special attention was paid to vertical and horizontal variations within stratigraphic units. In addition, emphasis was placed on obtaining detailed descriptions of glacial diamictons and their associated deposits. Other deposits, such as glaciolacustrine and glaciofluvial sediments, were studied in less detail. Although these sediments are stratigraphically important, more information is required for the stratigraphic correlation of diamictons than of these more laterally extensive and uniform deposits. Correlation of the latter can be aided by palaeomagnetic analysis, palynology, and (^{14}C) dating, whereas the the correlation of ancient glacial diamictons themselves is dependent mainly on field observations of sedimentologic and lithologic characteristics.

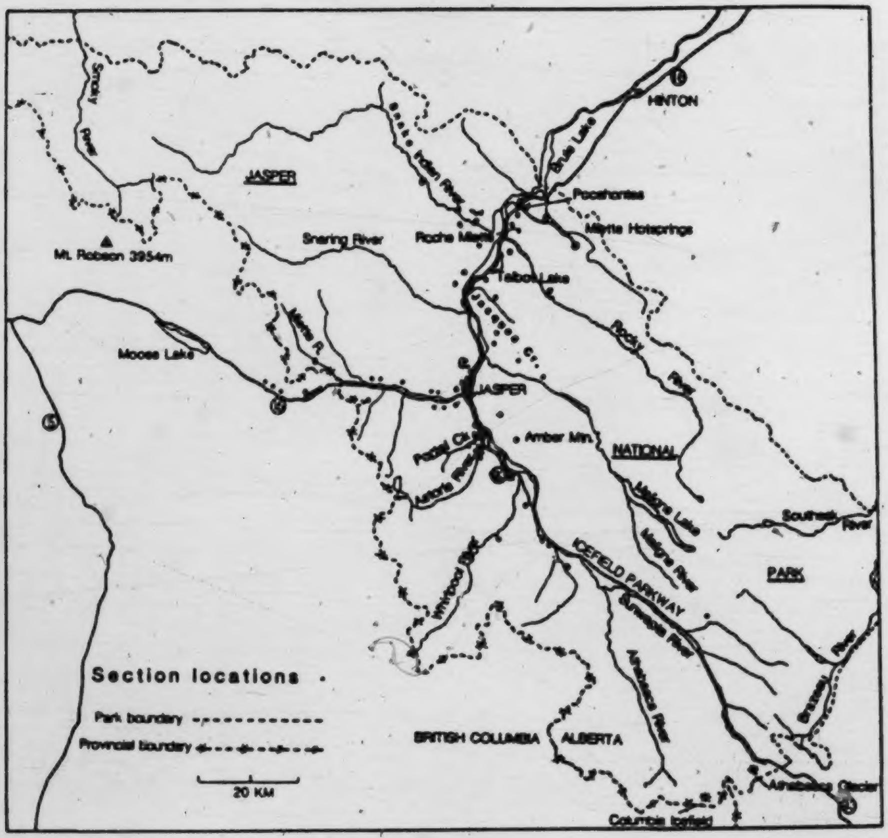
Due to the regional, field nature of this study, less emphasis was placed on laboratory analysis of the sediments than on the sedimentologic characteristics of the deposits observed in the field. The latter are often more important in genetic interpretation than are laboratory derived, physical and mineralogical characteristics. Sediment associations provide additional important evidence for environmental interpretations (Reading 1981). Consequently, the emphasis in this study is placed on observations on the spatial relationships (lateral and vertical facies changes) and internal characteristics (lithology and sedimentary structures) of the deposits rather than laboratory derived data which are more important for studies of a purely stratigraphic nature.

B. Field Descriptions

Surface and subsurface diamictons were described at about 75 localities in the Jasper region (Figure 4). Recent slump and colluvial deposits were not described. Exposures varied from shallow road cuts to river sections up to 100 m high and over 1 km long. Field descriptions included data on:

1. grain size distribution of matrix and clasts,

Figure 4: Map of section locations.



2. maximum and modal clast size
3. type of grain support (i.e. matrix or clast supported)
4. clast shape, roundness, and lithology,
5. abundance of striations, faceting and fracturing of clasts,
6. matrix color,
7. internal characteristics such as banding or shear structures,
8. sorting
9. sedimentary structures of associated sorted materials, such as type and thickness of stratification, dip and dip direction of beds and pebble imbrication,
10. shape, size, and abundance of sand and gravel lenses
11. compaction and cementation,
12. organic content,
13. lateral and vertical changes within units
14. geometry and distinctness of upper and lower contacts, and
15. surface form wherever possible.

Major section descriptions are provided in Appendix 1.

C. Identification and classification of glacial diamictons

General discussion

Diamictons of glacial origin were identified in the field by the presence of features such as glacially abraded (striated and faceted) clasts, clasts of erratic lithology, and bimodal or multimodal particle size distributions. These features are indicative of glacial transport and they are the main characteristics generally used to identify tills in the field (Dreimanis and Schluchter, 1985). Alluvial fan deposits and landslide debris do not exhibit such features. Instead they are derived entirely from adjacent mountain slopes and are comprised of angular clasts of local lithology. Complete descriptions of diamictons of this nature are included in Appendix 1. The problems of distinguishing some types of glacial and non-glacial diamictons has recently been discussed by Dreimanis and Schluchter (1985).

Present till classification systems are genetically based (Boulton, 1976; Dreimanis, 1976, 1982a; Haldorsen, 1982; and Shaw, 1982a) and, although they are useful in identifying the types of tills that may occur in an area, they require detailed field and laboratory observations. This is mainly because genetically different tills may have similar characteristics and are commonly indistinguishable without detailed study. Subtle differences in till characteristics often result in major reinterpretations of till type and depositional environment. Thus, the information required to make accurate genetic interpretations in the field is commonly not available. In addition, genetically based systems are continually evolving as new or more detailed information from modern glacial environments becomes available. As a result, deposits classified according to genetically based systems are continually subject to reclassification. For example, using a term like 'lodgement till' is not an objective approach but an interpretation and is therefore subject to revision. Even the term 'till' is now seldom used in the field because of its genetic implications and it has been replaced with 'diamicton'. Recent studies emphasizing the descriptive facies approach (Eyles and Eyles, 1983; Kulig, 1985; Proudfoot, 1985) have led to major reinterpretations of sediments traditionally thought of as tills deposited at the base of active glaciers.

Approach

From the field descriptions, glacial diamictons were subdivided into 8 major types. Identification of different types was based on characteristics which were:

1. as diagnostic of any one typ[illegible]ssible,
2. easily recognizable in the field, and
3. thought to be of ultimate importance for genetic interpretations.

Since most glacial diamictons in the Jasper region are massive and show little internal structure, classification was primarily based on the nature and structure of sorted and stratified materials which are commonly associated with the diamictons. These sediments may occur as lenses, pods, wisps, or thin beds or laminae within the diamictons or they may be complexly intercalated with them. Most of these forms of sorted material are less than one meter thick, often only centimeters or millimeters thick. Thicker sequences of stratified materials (in the order of meters) may be interbedded with, or grade laterally into, diamicton beds. Thus, categories were identified largely on the type, amount and geometry of these associated sorted and stratified sediments. In diamictons where characteristic internal structures, such as color or textural banding and high clast contents, were present, designations were also based on the internal characteristics of the diamictons themselves (see Chapter 3).

D. Pebble fabric analysis

Three-dimensional analyses of pebble orientations in diamictons were performed at 21 selected sites by measuring the trend and plunge of the long axes of blade and prolate shaped clasts in the medium to large pebble size classes. The a / b / c axial ratio of blade shaped clasts is 3 / 2 / 1. The axial ratios of prolates are a / b>2 and b is approximately equal to c. A minimum of 25 pebbles were measured at any one sample site. Fifty pebbles were measured at most localities. Fabric measurements were taken on individual beds within an area of one square meter or less wherever possible.

Fabric data were statistically analyzed by computer using a program developed by H.A.K. Charlesworth (Department of Geology, University of Alberta, Edmonton, Alberta). A similar program has been described by Mark (1971, 1973). Two types of three-dimensional orientation diagrams were produced, scatter (density) plots and contour diagrams. An equal area projection was used for both types of diagrams. Density contours were constructed using a counting circle to locate point concentrations which depart significantly from a uniform distribution (Kamb, 1959). The size of the counting circle (H) is determined by the simple formula H= 1 / N where N is the number of data points (Cheeney, 1983). Thus, for N=25, the size of the counting circle is equal to 4% of the area of the projection circle. For N=50, a 2% counting circle is used. In order to represent two dimensional patterns, the orientation data were also plotted on three types of rose diagrams; rose histograms, moving average rose diagrams and smoothed rose diagrams.

Eigenvalues (L) were calculated for three mutually orthogonal eigenvectors (V_1, V_2, and V_3). V_1 parallels the axis of maximum clustering of the pebble axes and thus represents the mean axis or primary mode of the fabric (Mark, 1974). V_3 parallels the axis of minimum clustering. The sum of the three eigenvalues ($L_1+L_2+L_3$) is equal to N. They are a measure of the degree of clustering around their respective eigenvectors (Woodcock, 1977). In this thesis they are presented in the normalized form (S) where

$$i = Li / N$$

and thus,

$$S_1 + S_2 + S_3 = 1.$$

For N = 50, S_1 values of 0.484 or greater indicates a non-uniform distribution at the 1% significance level. For N = 20, S_1 values greater than 0.575 are significant at the 1% level (Mark, 1973, 1974).

E. Laboratory Studies

Grain size analysis

Matrix textures of multiple representative samples from each described diamicton type were analyzed by the hydrometer method as described in ASTM D422 (1964). The sand, granule and pebble fractions were sieved following the procedures given in ASTM D423 (1964). The data were tabulated and presented graphically using a computer program developed by D. Wynne (Department of Geology, University of Alberta, Edmonton, Alberta). Statistical grain size parameters were determined using the formulas given in Folk (1974). The results of the grain size analyses are given in Appendix 2.

Pebble lithology

Samples for lithological analyses were taken from selected localities where the data would potentially be useful for stratigraphic and till provenance studies and for genetic interpretations. Pebbles in the medium to large size classes (8 - 64mm) were collected and analyzed in both the field and laboratory. The main lithologic groupings were carbonates (limestone and dolomite), fine clastics (shale, siltstone and mudstone), coarse clastics (quartzitic sandstone, arkosic sandstone, pebbly sandstone and conglomerate) and metamorphics (mainly schist). The results of the lithologic analysis are presented in Appendix 3.

III. Description, Classification and Interpretation of Sediment Types

A. Introduction

The methodology used to develop the classification scheme presented here is similar to the facies approach as it is based on objective criteria readily observable in the field (Walker, 1984). In a descriptive sense, the term "facies" is usually restricted to sediments of uniform lithology. However, many of the categories described below include diamicton as well as associated deposits and thus they should be termed facies associations. Consequently separate categories are designated "types" rather than "facies" to account for the more generalized level of classification required to include these associated deposits.

Eight diamicton types are defined on the basis of the nature of sorted and stratified materials associated with the diamictons, as well as on characteristic internal features of the diamictons themselves (mainly pebble fabric, banding, and grain size distribution of matrix and clasts). These criteria are similar to those used by other authors. Lawson (1981a), for example, identified 3 main criteria for distinguishing glacial sediments in the modern environment. These were pebble fabric, sedimentary structure (mainly of sorted and stratified sediments associated with the diamictons), and clast concentrations. These criteria have genetic implications and, since the ultimate intent of facies designations is to interpret and thus distinguish depositional environments (Walker, 1979), they are used in this study to designate different types.

Lawson (1981a) did not consider any of his three criteria as mutually exclusive for distinguishing the origins of glacial diamictons in the Matanuska Glacier area but stated that

> "due to the complex nature of sedimentation in the glacial environment these criteria should be used with other physical properties of the deposits, including overall texture, geometry, stratigraphic association, bed contacts and surface forms"

(Lawson, 1981a, p83). Consequently, complete descriptions are given wherever possible. Diagnostic criteria are listed first. Interpretations on depositional environment follow each description. Lateral and vertical variations within diamictons and stratigraphic relationships with other deposits were also of primary importance in making genetic interpretations. It must be emphasized that the interpretations are independent of the descriptions and are subject to revision. A summary of the characteristics and interpretations of each diamicton type is provided in Table 1.

B. Type 1: Massive diamicton

General Description

Massive diamicton with no apparent internal structures is by far the most common type of glacial diamicton in the Jasper area. Sand and silt lenses are rare. Type 1 diamicton locally occurs in thicknesses in the order of tens of meters (Plate 1a). Striated clasts are abundant with at least 35 - 50% of all shale and limestone clasts being striated. Clasts of local lithology dominate. The diamicton is generally very dense and compact and relatively fine grained (Figures 5 and 6). At its base, diamicton of this type may take on the textural characteristics of underlying sediments (Plate 1b). For example, the lower part of a diamicton overlying a sand and gravel unit in the Portal Creek area has a sandier texture than the diamicton immediately above (Figure 7).

Fabric diagrams for type 1 exhibit the strongest preferred orientations of all the diamicton types investigated in the Jasper region (Table 2 and Figure 8). Elongated clasts tend to be aligned parallel to the inferred direction of ice flow (Figure 9). The a-axes show either an upvalley plunge or no preferred plunge at all (Figure 10). Rose diagrams are strongly unimodal (Figure 9).

The lower contacts of diamictons of this type are usually planar (Plate 1c) and vary from sharp to gradational. Intraclasts sometimes occur at the base and underlying sediments are often deformed and eroded (Plate 1b). Deformation is usually of a compressive nature.

The occasional presence of sorted materials (constituting less than 5% of the total deposits) in type 1, allows for the distinction of two subtypes.

Table 1: Characteristics and depositional environments of glacial diamictons in the Jasper area

Type	Name	Characteristics	Genetic Interpretation
			Basal tills:
1	Massive diamicton	Fine grained, dense, massive, matrix-supported diamicton; striated clasts of local lithology common; strong, unimodal pebble fabric, parallel to the valley; sharp basal contact	Basally derived tills of indeterminate origin
1a	Massive diamicton with rare, steeply dipping, sand and gravel lenses and layers	Characteristics as in facies 1 but with a consistent downvalley plunge of sand lenses and a-axis of elongated clasts	Lee-side till
1b	Massive diamicton with rare, plano-convex, sand and gravel lenses	Characteristics as in facies 1 but with rare, horizontal, well stratified, plano-convex lenses	Basal melt-out till
2	Massive diamicton with abundant striated, faceted, and embedded clasts	Massive, dense, fine grained, diamicton; abundant heavily striated clasts; faceted, embedded and fractured clasts common; strong, unimodal, pebble fabric, parallel to valley; lower contact sharp and planar	Subglacial lodgement till
3	Banded diamicton	Diffuse, horizontal, diamicton bands (distinct mainly due to color and textural differences); bands may drape boulders; fine grained; low total clast content; unimodal, moderately strong, pebble fabric parallel to valley; lower contact gradational	Basal melt-out till

4	Massive diamicton containing sand and gravel lenses circular in cross section	Massive diamicton similar to type 1 but with sand and gravel lenses nearly circular in cross section (tubular sand bodies); stratification in lenses exibits normal faults and convolutions; moderate to weak, pebble fabric, unimodal to multimodal; lower contact gradational	**Englacial tills:** Melt-out till (from basal positions within ice)
5	Bouldery diamicton with numerous, highly disturbed, sand and gravel lenses and layers	Massive to weakly stratified diamicton; clasts of non-local lithology dominate; normally faulted, trough-shaped, sand and gravel lenses; irregular, thin, layers of sorted material; large angular clasts common; poorly compacted; intermediate matrix textures; moderate to weak pebble fabric (unimodal, bimodal or multimodal), high a-axis plunges; lower contact commonly gradational	**Supraglacial tills:** Flow till
			Icemarginal deposits-Proglacial (Frontal):
6	Massive to moderately stratified diamicton containing trough-shaped sand and gravel lenses	Matrix to clast-supported diamicton with numerous trough-shaped lenses and thin layers of sorted material; sorted beds may dip gently and are traceable for tens of meters; channel-fill cross-bedding common in lenses; lower contacts sharp to gradational	Till flow, debris flow, and fluvial deposits

6a	Intercalated diamicton, sand and gravel commonly with compressive deformation structures	Diamicton dominates; sorted layers indistinct and may exhibit low angle faults, overturned folds and/or shear(?) structures	Proximal proglacial till flows with intermittent fluvial deposits
6b	Diamicton with abundant undisturbed, trough-shaped, sand and gravel lenses	Diamicton less dominant than in 6a; abundant, regularly shaped, sand and gravel lenses; diamicton sandier than 6a; high upvalley a-axis plunges common	Distal, proglacial till flows with intermittent fluvial deposits
			Icemarginal deposits-Proglacial and Lateral:
7	Coarse textured diamicton interbedded with sands and gravels	Massive to moderately stratified diamicton; high total clast contents; sand and gravel beds dominate; lower contacts conformable or erosional	Subaerial debris flow deposits and glaciofluvial outwash
7a	Sandy diamicton interbedded with sands and gravels	Matrix-supported, sandy diamicton; some striated and subangular clasts; sands and gravels exhibit large changes in grain size distribution, sorting and bed orientation over short distances; load and fluid injection structures common	Proximal flow till and subaerial debris flow deposits and ice-contact outwash
7b	Gravelly diamicton interbedded with sands and gravels	Gravelly, clast-supported, diamicton grades into moderately sorted gravels ; sands and gravels generally horizontally bedded and well sorted	Subaerial debris flow deposits and proximal outwash
8	Massive diamicton interbedded with horizontally laminated silts and clays	Matrix-supported, fine grained, diamicton; occasional convolute laminations; scattered pebbles in silts and clays; lower contacts irregular	Subaquatic flow tills and glaciolacustrine sediments

Plate 1a: Massive diamictons (Dm) of type 1.

Plate 1b: Type 1 diamicton (Dm) overlying sands (S) and gravels (G); note inclusions of sandy material (Sr) in the diamicton and deformation in the underlying sands and gravels.

Plate 1c: Type 1 diamicton (Dm) overlying horizontally stratified sands, S(h), and gravels, G(h); note the sharp, planar, lower contact of the diamicton.

Plate 1d: Massive diamicton of subtype 1b with plano-convex sand, S(h), and gravel, G(h), lenses.

A

B

C

D

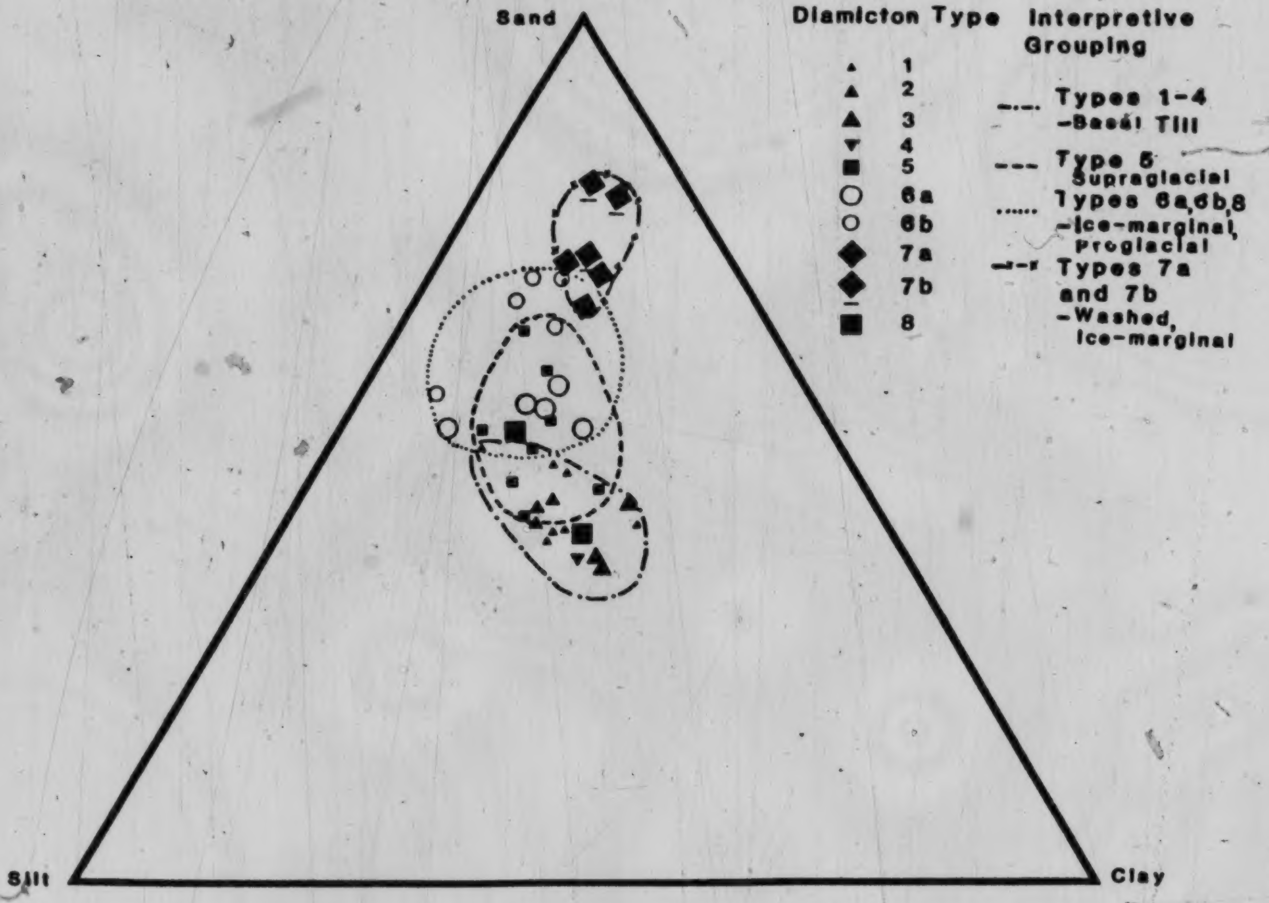


Figure 5: Representative matrix textures of diamicton types 1-8

Figure 6: Textural analysis of bulk samples from diamicton types 1-8

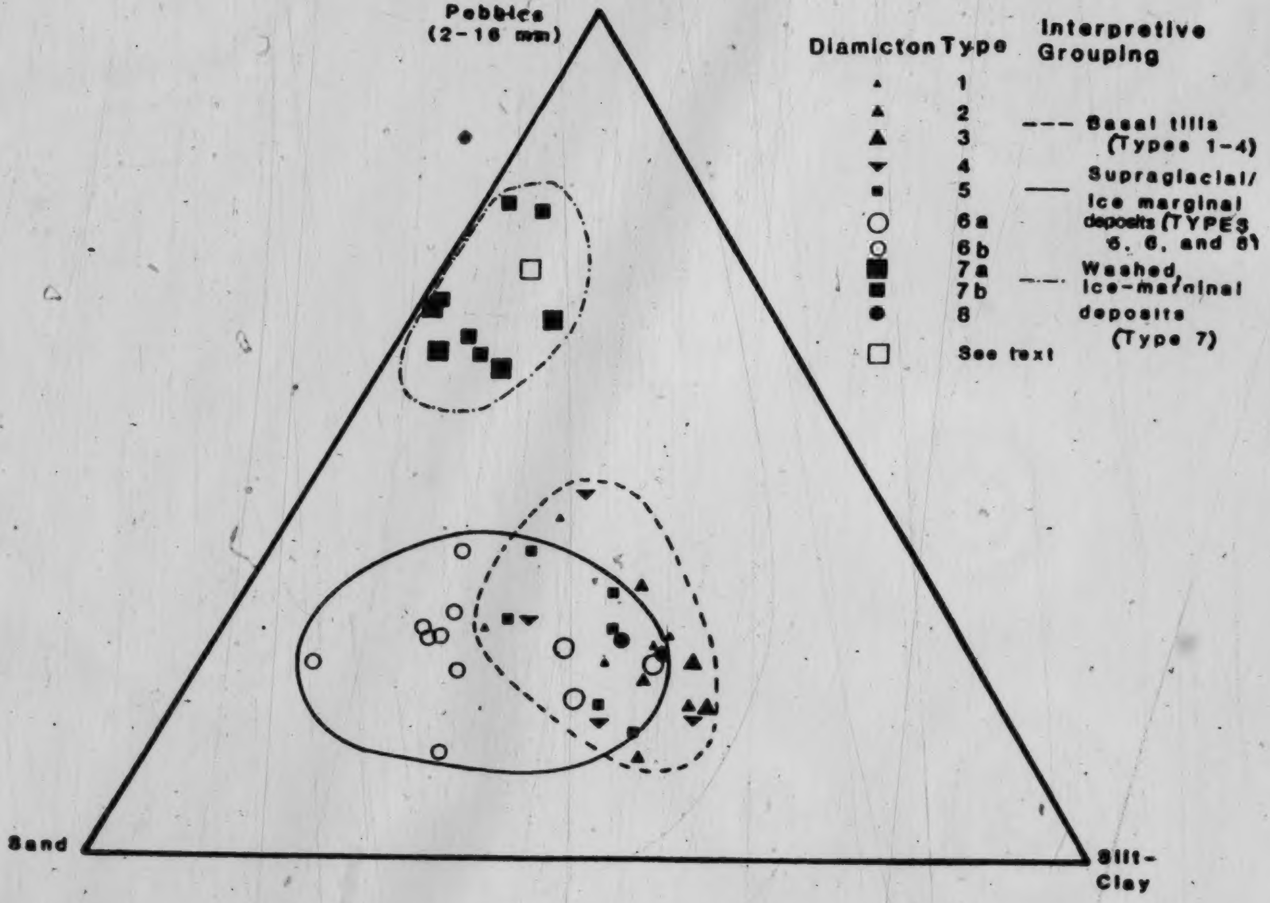


Figure.7: Vertical Variation in Grain Size Distribution in Diamicton-Type 1.

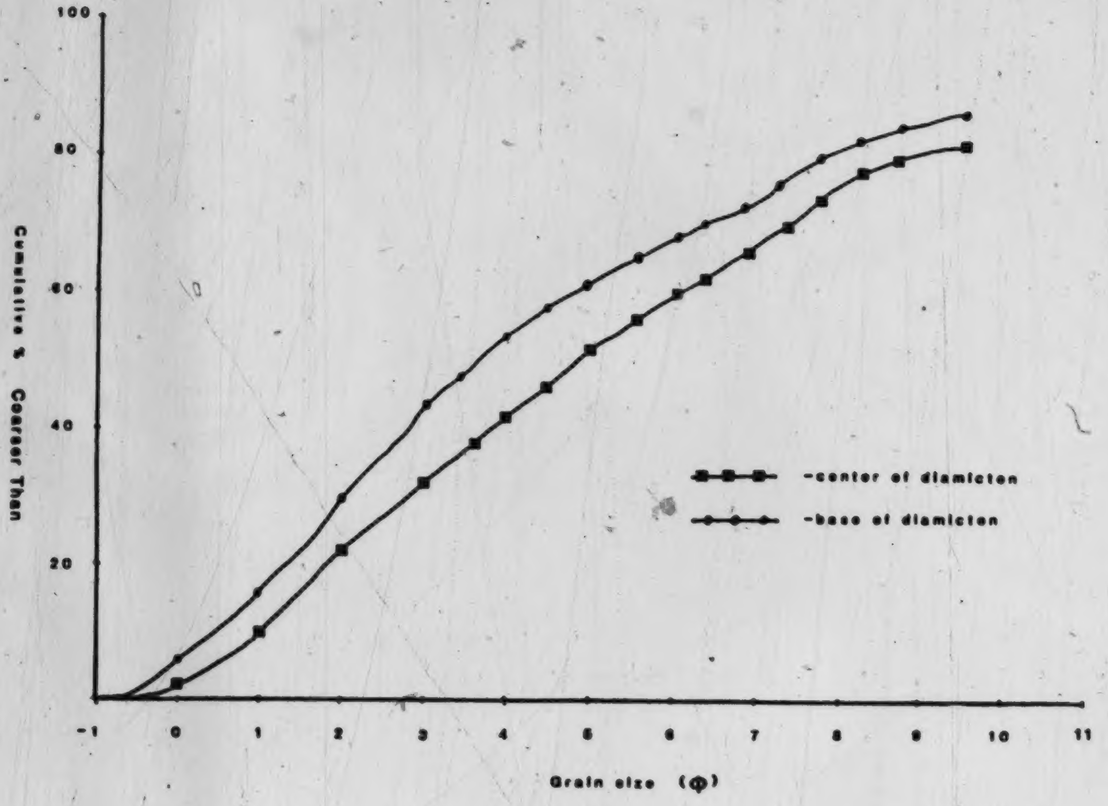


Table 2: Fabric Data for Till Types 1-6

TYPE	SAMPLE #	TREND (°)	PLUNGE (°)	EIGENVALUE/N		N	Up-valley orientation (°)
				S_1	S_3		
1	83-5-3	348.4	0.6	0.78	0.06	25	150
1	83-18-13b	220.8	10.0	0.74	0.04	25	225
1a	83-29-4l	0.4	11.0	0.67	0.06	50	150-250
1a	83-29-4la	349.1	5.9	0.6	0.08	25	150-250
1a	83-29-4lb	5.7	14.6	0.75	0.06	25	150-250
1b	83-27-3	192.8	1.1	0.68	0.09	50	190
1b	83-27-3a	10.8	5.3	0.70	0.09	25	190
1b	83-27-3b	195.0	7.6	0.67	0.07	25	190
1b	83-13-2-v	77.2	2.7	0.67	0.1	25	210-300
2	83-11-3b	9.6	11.5	0.64	0.14	25	120-220
3	83-11-3a	162.4	2.0	0.57	0.15	25	120-220
3	83-29-4a	353.0	5.0	0.55	0.02	25	150
3	83-29-4b	339.0	5.5	0.55	0.10	25	150
4	83-5-3a	153.8	7.6	0.50	0.16	25	150
5	83-29-5	63.0	7.2	0.56	0.11	50	250
5	83-27-1	181.0	13.4	0.47	0.12	50	190
5	83-18-13	126.3	2.6	0.55	0.07	25	225
6a	83-29-1	161.0	2.7	0.49	0.09	50	250
6a	83-1-4	6.0	1.3	0.65	0.13	50	200
6b	83-13-2	282.3	24.5	0.49	0.16	25	210-300

Figure 8: Eigen value relationships of pebble fabrics from diamicton types 1 to 6

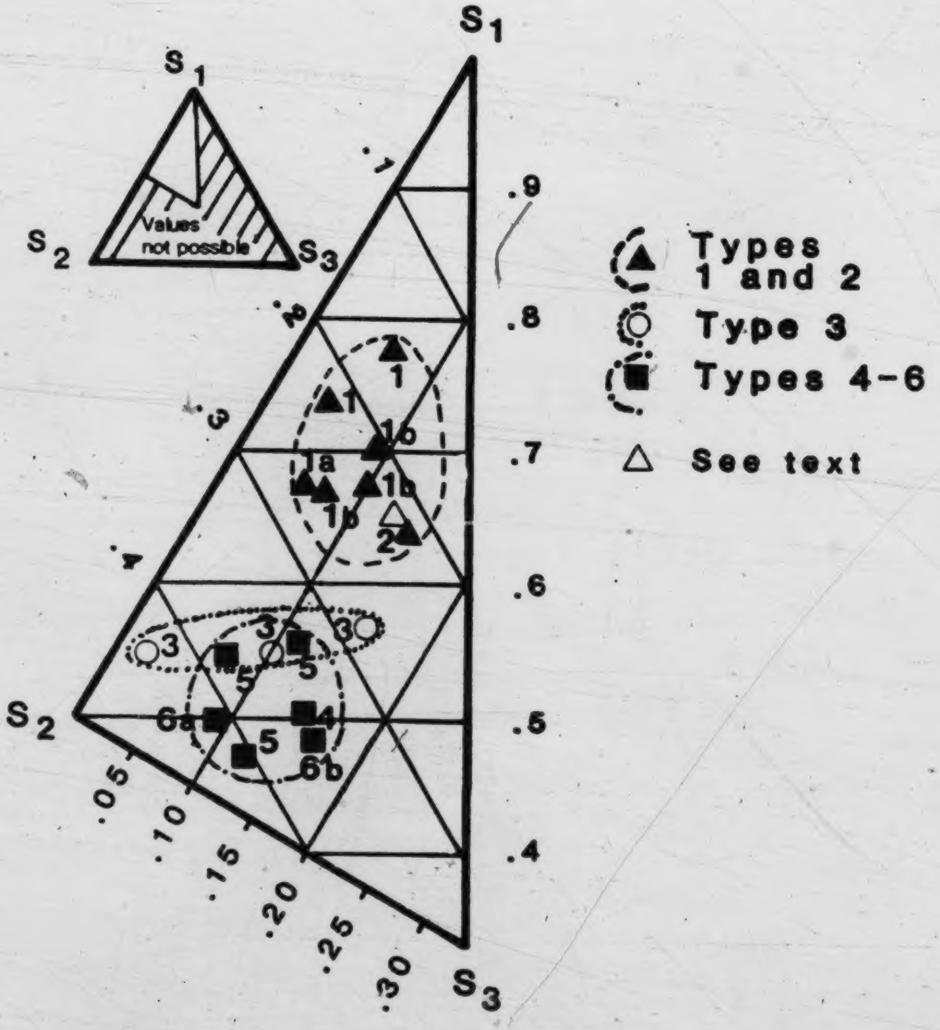
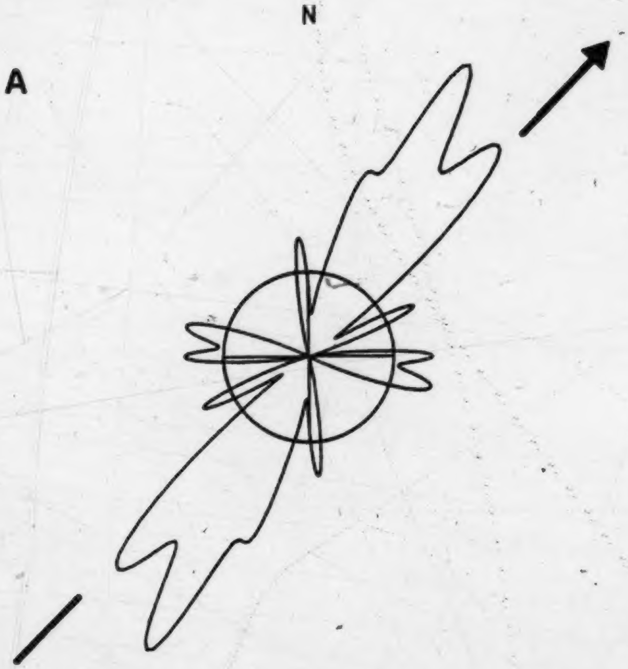


Figure 9: Rose diagrams representing two dimensional pebble orientations in diamictons of type 1, (N=25); Arrows point downvalley. a) Pocahontas area (Section 83-18); b) Rocky River area (Section 83-5).

SMOOTHED ROSE DIAGRAM.   K = 200   N = 25

SECTION 83-18B POCAHONTAS



SECTION 83-5 UNIT 3 ROCKY

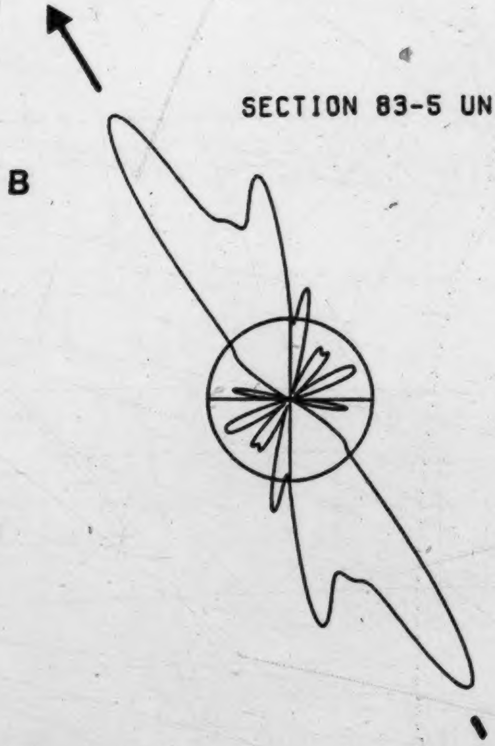
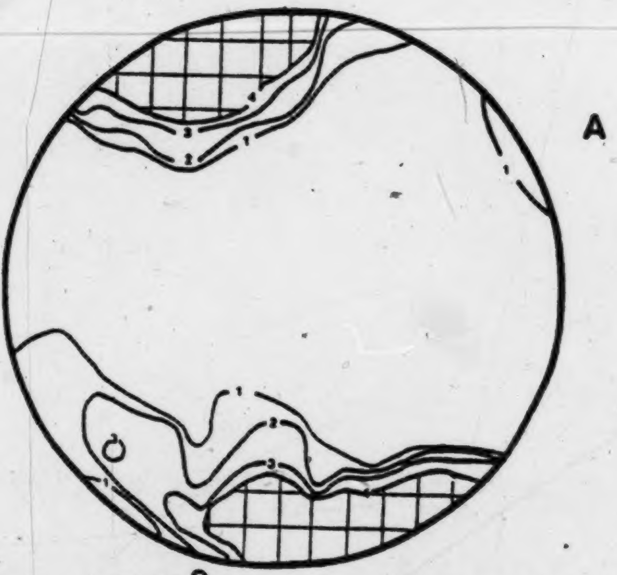
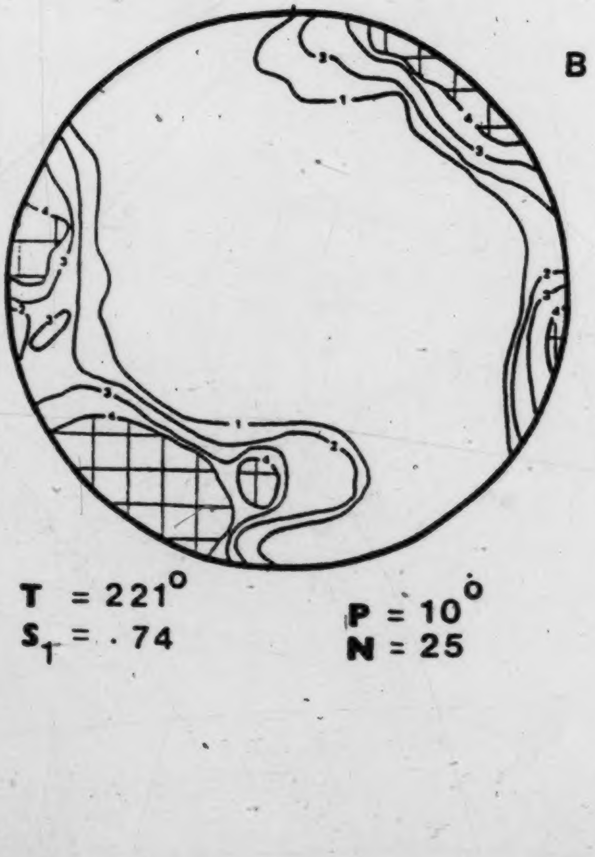


Figure 10: Three dimensional representation of pebble orientations in type 1 diamictons; a) Rocky River Valley (Section 83-5); b) Pocahontas area (Section 83-18). (Equal-area projection; contours represent number of points in 4% area of hemisphere.) T and P give the trend and plunge of the principle eigenvector, V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured.



T = 348°
S_1 = .78

P = .6°
N = 25



T = 221°
S_1 = .74

P = 10°
N = 25

Subtype 1a: Massive diamicton with rare, steeply dipping sand and gravel lenses and layers

In subtype 1a, sands and gravels occasionally occur within otherwise massive diamicton as thin lenses and layers which have dips in the order of 10° to 30°. Dip directions are invariably downvalley. Three dimensional fabric analyses indicate that the a-axes of elongated pebbles also dip preferentially in a down valley direction (Figure 11a). The plunge of the principal eigenvector is generally quite high (Table 2). The dip of sand and gravel layers and the a-axis plunge of pebbles are generally similar. Both tend to decrease at higher levels within continuous exposures of this subtype. Other than the presence of the dipping sand and gravel lenses and the preferred pebble fabric plunge, diamictons in this subtype exhibit the same internal characteristics as those in type 1 described above. Pebble fabrics are strongly unimodal or slightly bimodal (Figure 12). Subtype 1a is common downvalley of bedrock obstructions.

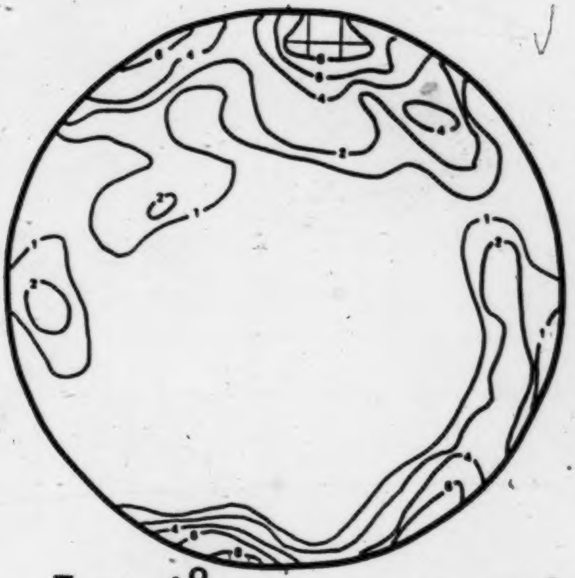
Subtype 1b: Massive diamicton with rare, plano-convex, sand and gravel lenses

This subtype is characterized by sand and gravel lenses which occur occasionally at the base of massive (type 1) diamictons(Plate 1d). The lenses have strongly to slightly convex upper surfaces and planar to slightly trough-shaped lower surfaces. Lenses of a similar shape have been termed plano-convex lenses (Shaw, 1982). Undisturbed stratification is often present in the lenses, usually in the form of horizontal, planar or trough cross-bedding. Bedding usually is conformable with the lower boundaries of the lenses. Contacts between sand lenses and diamicton vary from sharp to gradational. Texturally and structurally this subtype is similar to type 1 but tends to be more variable than type 1. Large clasts with numerous striations are relatively abundant.

Tills of this subtype exhibit well developed pebble fabrics (Figure 13) oriented parallel to the inferred direction of ice movement (Table 2). The long axis of elongated clasts generally have a shallow upvalley plunge (Table 2 and Figure 11b).

Figure 11: a) Three dimensional representation of pebble orientations in type 1a diamicton (Section 83-29). (Equal-area projection; contours represent number of points in 4% area of hemisphere.) b) Three dimensional representation of pebble orientations in type 1b diamicton (Section 83-27). (Equal-area projection; contours represent number of points in 2% area of hemisphere.) T and P give the trend and plunge of the principle eigenvector, V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured.

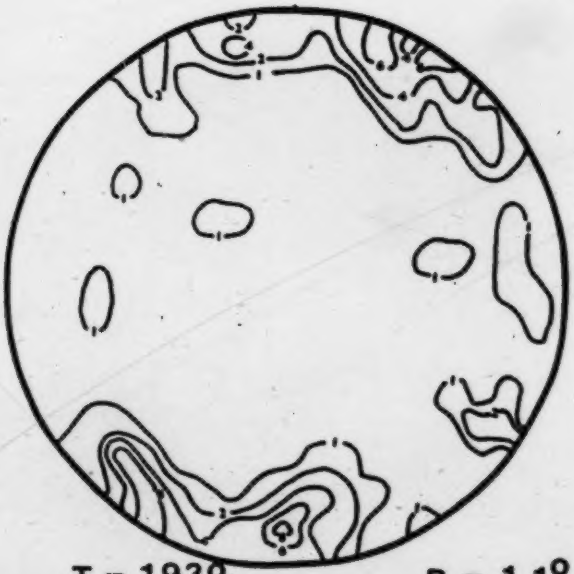
A



T = .4°
S_1 = .67

P = 11°
N = 50

B



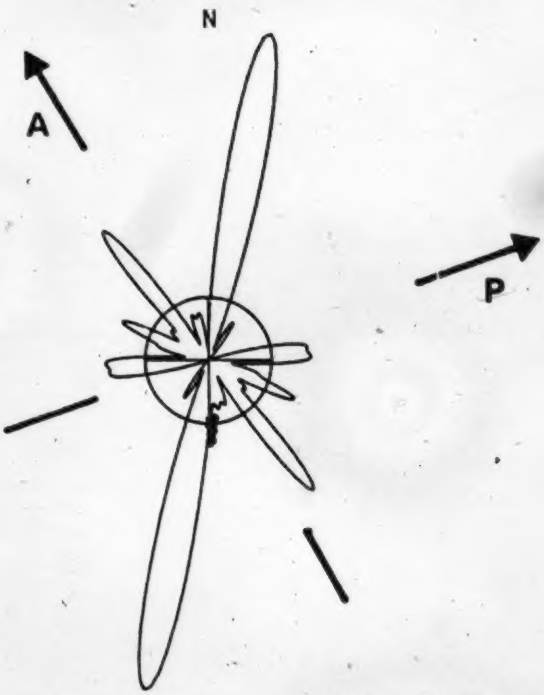
T = 193°
S_1 = .68

P = 1.1°
N = 50

Figure 12: Rose diagrams representing two dimensional pebble orientations in diamictons of type 1a (N=25) near the junction of the Portal Creek and Athabasca River valleys (Section 83-29). Arrows point down the Athabasca (A) and Portal Creek (P) valleys.

SMOOTHED ROSE DIAGRAM.   K = 200   N = 25

SECTION 83-29 UNIT 4A-L PORTAL



SECTION 83-29   UNIT 4B-L PORTAL

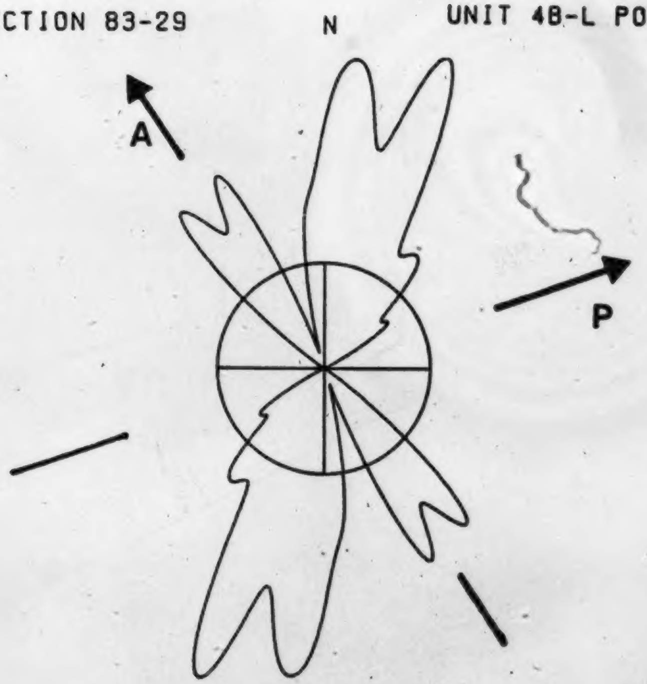
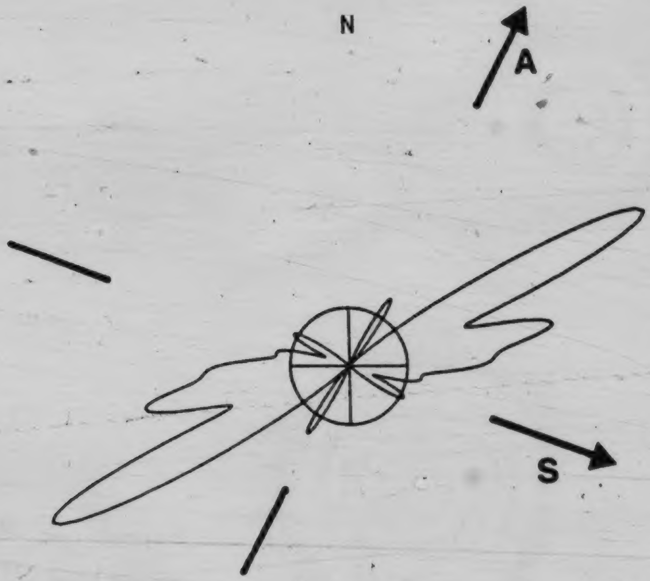


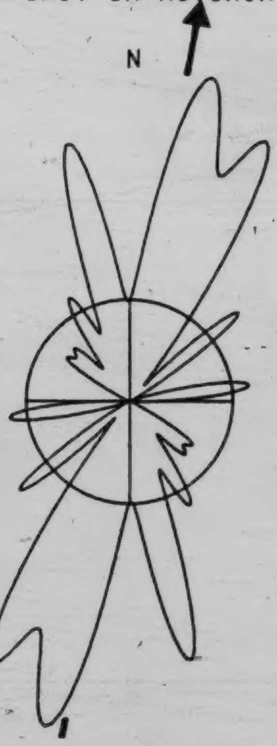
Figure 13: Rose diagrams representing two dimensional pebble orientations in diamictons of type 1b; arrows point downvalley; (N=25); a) locality near the junction of the Athabasca and Snake Indian River valleys; A - Athabasca Valley, S - Snake Indian River Valley (Section 83-13). b) Astoria River valley (Section 83-27).

A SMOOTHED ROSE DIAGRAM. K = 200 N = 25

SECTION 83-13-2-V SNAKE INDIAN



B SECTION 83-27 UNIT 3A ASTORIA



Interpretation

Type 1

The abundance of striated clasts and the fine matrix textures indicate that diamictons of this type are basal tills. Transport of debris at the base of a glacier results in comminution producing striated clasts and relatively fine textured matrices (Haldorsen, 1982). The dominance of local lithologies and the presence of strong, unimodal, pebble fabrics parallel to the valley support this interpretation.

Although the above characteristics provide good evidence for basal transport, the actual mechanism of deposition cannot be determined without further information (see discussion of types 1a and 1b). However, the strongly developed pebble fabrics parallel to the valley and the very dense, compact nature of the tills indicate that little or no movement occurred after till formation. This suggests that the tills are primary or otho-tills (Dreimanis, 1982a) and that lodgement and meltout processes may have been largely responsible for the deposition of this type (Boulton, 1976; Dreimanis, 1976; Shaw, 1982; Haldorsen and Shaw, 1982). The presence of active ice prior to deposition is indicated by the erosional nature of the lower contact and by the incorporation of sediments from underlying deposits. The above interpretation is supported by the compressive deformation in the underlying sediments and by the presence of intraclasts believed to be rip-ups eroded by the overriding ice. Shaw, (1982) observed similar characteristics in basal tills in the Edmonton area.

Subtype 1a

Diamictons of this subtype are interpreted as tills deposited in the subglacial environment in pre-existing depressions formed by bedrock topography. The most common type of bedrock depressions are narrow valleys cut by tributary streams which flow partially across major valleys. Most tributary valleys in the Jasper region today are presently eroding bedrock in at least part of their reaches and have cut relatively narrow channels compared to the main valleys which they flow into. In previous interglacials a similar geomorphic situation probably existed as evidenced by the thick glacial fill in many partially excavated buried valleys.

During glacial periods the larger volume of ice in the main valleys would eventually override the valleys cut by tributary streams in the area where the two valleys intersect (see chapter 4). Assuming that the tributary valley had not been filled by other deposits (eg. outwash, proglacial debris flows, etc.) prior to the advance of main valley ice over the area, then a subglacial bedrock depression would exist, generally oriented perpendicular to the direction of ice flow.

The dip of sand and gravel lenses and layers and the preferred plunge shown on pebble fabric diagrams of this type (Figure 11a) may be the result of deposition of material along the inclined walls of pre-existing bedrock depressions formed by transversely oriented tributary valleys. The decrease in dip that generally occurs upsection, supports this interpretation since the slope of such depressions would decrease as they were gradually filled (see chapter 3).

The depositional environment within these transverse tributary valleys would be similar to that in 'lee-side localities' as described by Haldorsen (1982). Haldorsen found that tills deposited in lee-side localities had the following characteristics:

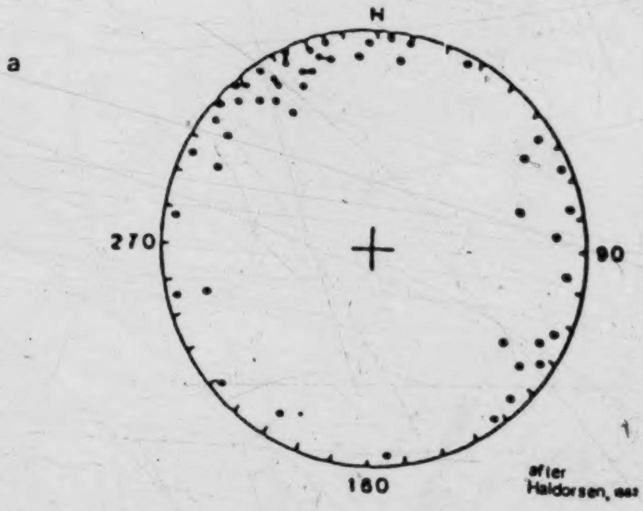
1) abundant surface and subsurface boulders,
2) sandy matrices,
3) angular clasts,
4) clear evidence of a local source with many clasts traceable to the nearest up-ice bedrock exposure, and
5) homogeneous textures.

These characteristics were attributed to local erosion and a short distance of transport.

Similar characteristics were found in tills of subtype 1a in the Jasper region except that matrix textures were finer and clasts less angular than in Haldorsen's study. These differences are attributed to the soft shale bedrock in valley bottoms in the Jasper area which is easily eroded, shaped, and broken down into finer particles. Till fabrics on the lee-side tills (Figure 14a) studied by Haldorsen (1982) are very similar to those of subtype 1a (Figure 14b). Haldorsen (1982) did not find lenses of sorted materials in the lee-side tills at Astadalen (Norway) but their presence in this subtype is not considered to preclude a similar origin.

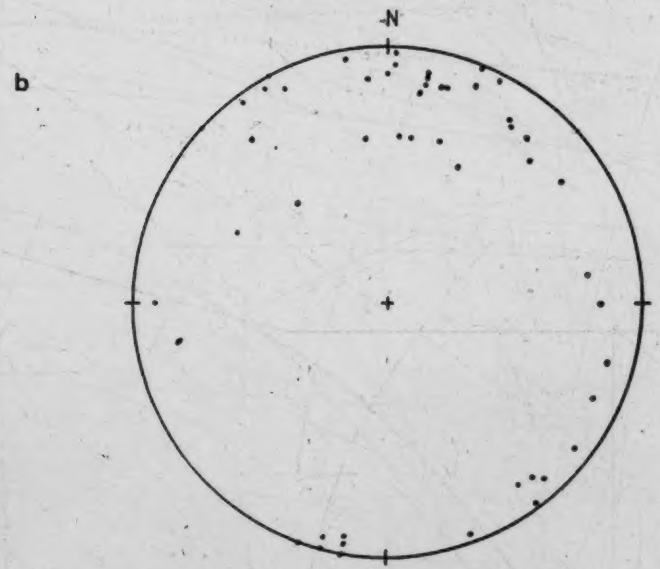
There are at least three possible mechanisms for the deposition of lee-side tills. Boulton (1971) observed considerable accumulations of till in cavities under Svalbard glaciers on the down glacier side of bedrock knobs. He noted that "thin till was oozing out

Figure 14: Comparison of scatter diagrams from lee-side tills a) described by Haldorsen (1982); and b) from type 1a diamicton in the Portal Creek Valley (Section 83-29). T and P give the trend and plunge of the principle eigenvector, V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured.



after
Haldorsen, [illegible]

T = 322 P = 4
S_1 = 0,68 n = 50



T = 0.4 P = 11
S_1 = 0.67 n = 50

like toothpaste from the ice/bedrock contact, to slump and slide down the lee-side of the knob" resulting in massive deposits with "only a very indistinct bedding" (Boulton. 1971, p. 63.). Some sorting did occur due to water moving down the slope. Pebbles tended to lie with their long axes parallel to the slope direction.

If transversely oriented tributary valleys in the Jasper region were narrow enough to prevent grounding of basal ice then subglacial cavities similar to those described by Boulton (1971) may have developed. Such cavities would become depositional sites for:

1. streams flowing at the base of the glacier, leaving lenses (channels) of sorted material, and
2. subglacial debris flows, leaving deposits similar to diamictons of subtype 1a.

The flowing of debris into an open cavity as an origin for this subtype is supported by the preferred plunge and relatively low S_1 values exhibited by pebble fabrics. However, the rarity of lenses of sorted sediment indicates that another origin is also likely since it is highly probable that meltwaters flowing in subglacial channels and rills would have existed in the cavities and deposited significant amounts of sorted material.

Two other possible depositional origins for lee-side tills were discussed by Haldorsen (1982) who interpreted the deposits found at lee-side localities as both basal meltout and lodgement tills with a gradation between the two genetic types. Lodgement tills were characteristically silty, compact tills with abraded boulders and cobbles and a marked a-axis orientation parallel to the last direction of ice movement. Haldorsen (1982) found it very difficult to find the boundary between lodgement and meltout tills in lee-side localities and found that some deposits showed characteristics of both.

All three of the above mechanisms (flow in a subglacial cavity, lodgement and meltout) could result in the fabric pattern characteristic of lee-side tills as they all would reflect pre-existing topography. A major factor controlling depositional mode would be the presence or absence of a subglacial cavity.

There is evidence in the Jasper region that all three processes operated in the deposition of subtype 1a. To illustrate this, a detailed discussion of a "lee-side" locality is required. Such a locality occurs along Portal Creek, a tributary stream of the Athabasca River forming a narrow valley transverse to the Athabasca valley. Since bedrock depressions of this type (i.e. those oriented transversely to the regional ice flow direction) are very common in the Jasper area and form one of the most significant depositional environments in the region, a detailed discussion of the Portal Creek locality (Section 83-29, Appendix 1) is provided separately in Chapter 3.

Subtype 1b

Diamictons of subtype 1b are interpreted to be basal meltout tills. Some deposition by lodgement processes may also occur but no unequivocal evidence for this was found. The fine textures, abundance of striated clasts and good fabrics indicate deposition at the base of a glacier (Boulton, 1976; Dreimanis, 1976; Kruger, 1979; Haldorsen, 1982; Haldorsen and Shaw, 1982). The plano-convex sand and gravel lenses which occur at the base of this subtype are interpreted as subglacial stream deposits. Sand lenses have been commonly reported in meltout tills (Harrison, 1957, Kruger, 1979, Haldorsen and Shaw, 1982, Haldorsen, 1982, and Shaw, 1982). The geometry of the lenses is very similar to subglacial channels formed in the phreatic zone of temperate glaciers (Shreve, 1972). The curvature of the tunnel ceilings can be highly variable and increases with the rate of melting which is induced by advected and frictional heat from the stream and circulating air in the tunnels (Shreve, 1972).

Shaw (1982) described plano-convex lenses of sand and gravel at the base of tills in the Edmonton area. He interpreted the lenses to be the result of bed load sedimentation in subglacial tunnels. The tunnels were formed by subglacial meltwaters that eroded upwards into the ice. The sharp upper contact of the lenses and the draping of diamicton over them suggested that the till was deposited by melt-out of the debris rich ice into which the tunnels were cut (Shaw, 1982). Shaw indicated that the tunnels need not have been choked with sediment for the sharp contact to be preserved, provided that the ice settled to the sediment surface after abandonment of the channel (although this would not explain the strong convex shape of the upper surface of some lenses).

The similarity of sand lenses of this type to those described by Shaw (1982) suggests that their associated diamictons are also basal meltout tills. The dense, compact nature of the diamicton, abundance of striated clasts, and fine textures also suggests this origin (Haldorsen, 1982, Haldorsen and Shaw, 1982, and Shaw, 1982) as does the moderately well developed pebble fabric which shows a shallow, upvalley, preferred plunge (Lawson, 1979b).

C. Type 2: Massive diamicton with abundant striated, faceted and embedded clasts

Description

Massive diamictons containing abundant , heavily striated, faceted and embedded clasts occur sporadically in the Jasper region. The main distinguishing characteristic is the presence of abundant striated clasts. Although other massive diamictons (eg. types 1a and 1b) contain numerous striated clasts, the percentage of striations on individual clasts and the total number of striated clasts is noticeably higher in this type. Between 70% and 90% of all lithologically soft rocks (mainly limestone and shale) are heavily striated compared to approximately 20-50% in other massive diamictons. Striations, particularily those on upper faceted surfaces, are almost always are oriented in the direction of ice movement (Plate 2a) as determined by other evidence (eg. fabric studies, flutings, drumlins and valley orientation). Striations on clasts with b/a ratios (diameter of intermediate to long axes) of about 0.6 or less generally are oriented parallel to the a-axis. Clasts with higher b/a ratios may show two sets of striations which generally occur at right angles, roughly parallel to the a and b axes.

Clasts with well developed faceted surfaces are also relatively abundant (Plate 2a). Faceting is invariably heaviest on upper surfaces, less pronounced or absent on lower surfaces, and rare on the sides of clasts. Many striated clasts are prolates (barrel shaped) and heavily faceted clasts are bullet shaped (Boulton, 1978; Kruger, 1984). Bullet shaped clasts commonly point (taper) upvalley.

Clasts 'embedded' in underlying deposits are another frequent characteristic of this type. 'Embedded' clasts are those which have the appearance of being partially buried in underlying deposits, but their upper surfaces are always in contact with massive diamicton or exposed at the surface. Where the underlying sediments are stratified they are clearly disturbed in the vicinity of the embedded clast. Deformation is of a compressive nature (folds and thrust faults) and suggests that the clasts were pressed or pushed into the underlying deposits.

Diamictons of this type are highly variable in nature. They may be dense and very compact with a fine grained (clayey to silty clay) matrix (Figure 5). In other localities the matrix is sandy. In some outcrops the matrix is absent or occurs only in small quantities in

Plate 2a: Striations on upper faceted surface of a large clast in type 2 diamicton; striations are oriented parallel to the valley.

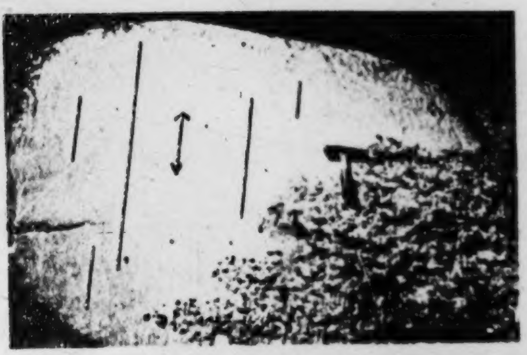
Plate 2b: Visible fabric (right-left) in diamicton type 2.

Plate 2c: Type 2 diamicton; note concentration of clasts at base of photo (Dc,m) and small gravel lens (sheared?) in photo center (G).

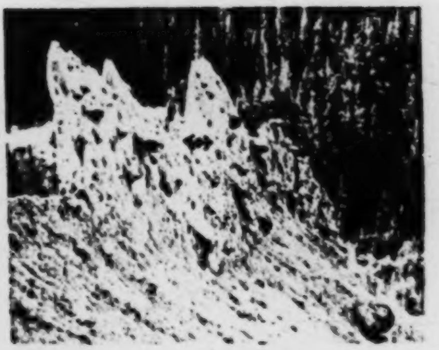
Plate 2d: Sharp planar contact between massive diamicton (Dm) of types 1 and 2 and sands (S) and gravels (G).

Plate 2e: Erosional contact between massive diamicton (Dm) of types 1 and 2 and horizontally bedded gravels (G).

A



B



C

D

E

voids in a clast-supported diamicton (Plate 2c). Locally this type is represented only by one or more striated and embedded clasts or by a thin layer of diamicton at the base of associated deposits. Clasts are frequently fractured, especially where they are in contact with one another or where clast contents are high.

Pebble fabrics on diamictons of this type were difficult to obtain due to their general thinness and sporadic occurrence. Elongated clasts generally were found to be oriented parallel to the valley and exhibit a near horizontal or slight upvalley dip. A strong parallel fabric was sometimes noticeably apparent in section (Plate 2b). At one locality, Jacques Creek (Section 83-11, Appendix 1), a moderately strong transverse fabric was obtained (Figure 15a). Many of the clasts were fractured and virtually all were heavily striated.

This type often overlies alluvial fan, glaciolacustrine, or glaciofluvial deposits. Fractured clasts are also common in these deposits, particularily when they are clast-supported gravels. The contact with these materials is invariably sharp and planar (Plate 2d). Truncation of bedding in the underlying sediments indicates that the contact is erosional (Plate 2e). This type usually underlies massive diamictons (type 1).

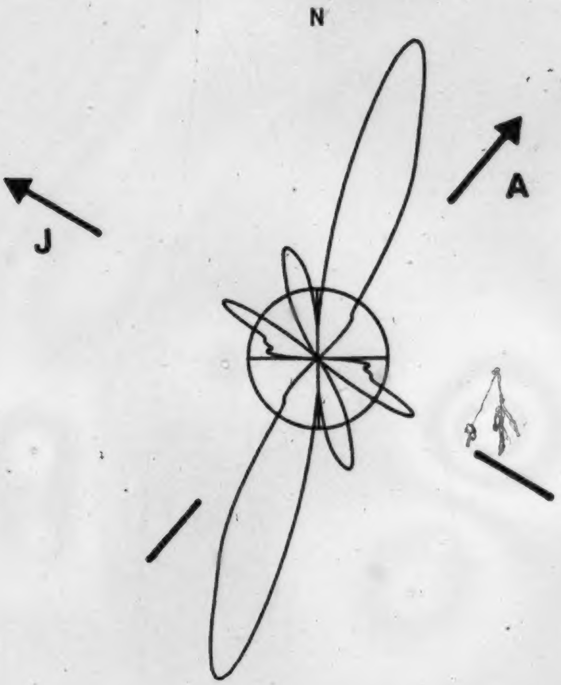
Interpretation

This type is interpreted as subglacial lodgement till. It forms as the result of pressure melting of debris rich basal ice against bedrock obstructions or increased frictional drag between particles that are in traction in the glacier sole and subglacial materials (Boulton, 1970, 1975). The presence of abundant striated, faceted and embedded clasts supports this interpretation (Kruger, 1979). "Embedding" of clasts is interpreted as a lodgement process as indicated by the compressive deformational structures which occur in stratified sediments underneath the clasts (Boulton, 1970, 1975; Kruger, 1979). The common bullet and barrel shapes of embedded clasts further supports this interpretation (Boulton, 1978; Kruger, 1984). Faceting and striations on the upper surfaces of lodged (embedded) clasts are probably the result of continued movement of debris rich ice over the clasts after initial deposition. The rarity of striations on the sides and bases of the clasts further suggests that they were lodged into the underlying materials leaving only the upper surfaces exposed to further abrasion.

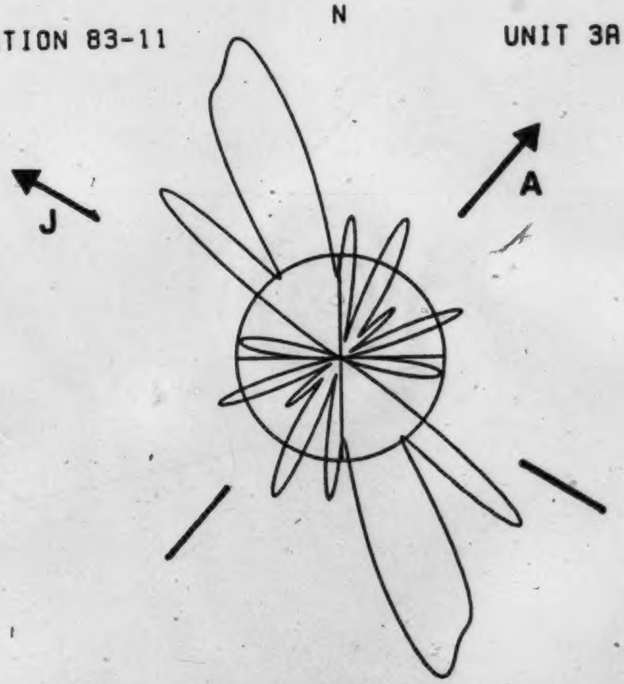
Figure 15: a) Rose diagrams representing two dimensional pebble orientations in diamictons of; a) type 2; and b) type 3, near the junction of the Jacques Creek and Athabasca valleys (Section 83-11); (N=25); Arrows point down the Athabasca (A) and Jacques (J) valleys.

A SMOOTHED ROSE DIAGRAM. K = 200 N = 25

SECTION 83-11 UNIT 3B JACQUES



B SECTION 83-11 UNIT 3A JACQUES



Boulton (1975) showed that clasts in traction at the base of a glacier may become lodged as a result of collision with clasts in the underlying sediments. He noted that this process may produce clusters of clasts and non-homogeneous tills with variations in sorting and fabric strength. Tills of this nature with locally high clast concentrations are typical of type 2. Fracturing of clasts in contact with each other at the base of this type and in immediately underlying materials may be the result of compressive forces induced during the lodgement process and by the weight of the overlying ice.

Unimodal fabrics with strong preferred orientations parallel to the direction of ice movement are typical of lodgement tills (Harrison, 1957; Lindsay, 1970; Boulton, 1971, 1975, 1976; Dreimanis, 1976; Kruger and Marcussen, 1976). Kruger (1979) and Rees (1983) found that strong pebble fabrics perpendicular to the ice flow direction may also develop in lodgement tills subjected to shearing forces. Boulton (1970) noted that stone-orientation fabrics in basal debris bands developed a transverse peak as a result of compressive flow of the glacier over bedrock obstacles. The transverse fabric shown in Figure 15a may reflect the compressive flow conditions that likely existed as a result of confinement of ice in the Jacques Creek (Figure 2) by the Athabasca glacier down valley from the sample site.

D. Type 3: Banded diamicton

Description

The main diagnostic characteristic of this type is the presence of horizontal bedding or bands within otherwise massive diamicton (Plates 3a and 3b). The bands are commonly 10 to 20 cm thick and are composed of diamicton with a grain size distribution either finer or coarser than the encasing diamicton. They are not composed of well sorted materials and do not exhibit any internal sedimentary structures such as graded bedding, cross-bedding, or planar laminations. They lie in a horizontal or slightly undulatory plane. Occasionally the bands appear to drape over underlying boulders without showing any corresponding decrease in band thickness (Plate 3c). Individual bands are sometimes laterally traceable for tens of meters. They generally have diffuse upper and lower contacts.

Plate 3a: Banded diamicton (type 3) in Jacques Creek valley.

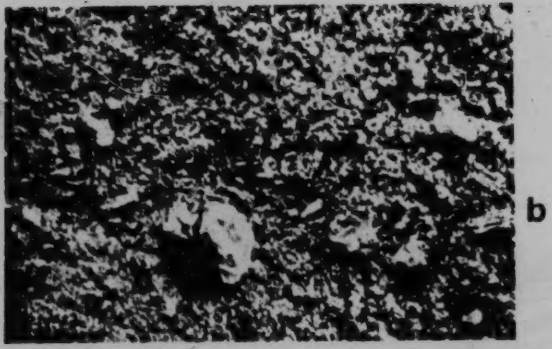
Plate 3b: Banded diamicton (type 3) in Portal Creek valley.

Plate 3c: Detail of diamicton band (b) shown in Plate 3b; note draping of band over large clasts; arrow points to hammer for scale.

A

B

C



Banded diamictons are rare in the Jasper region, being observed only at a few localities (Jacques Creek, Section 83-11, Appendix 1; Portal Creek, Section 83-29, Appendix 1, Figure 2). At these localities the bands are generally finer textured than the surrounding diamictons (Figure 16), but matrix textures within the bands themselves are quite variable. Clast content within the bands is also variable, being up to 60% (average 25%) at Portal Creek but only 5-10% at Jacques Creek. At the latter locality clast contents in the encasing diamictons are generally from 30 to 60%. The distinct appearance of the bands is also due to differences in color(Plate 3) and possibly also mineralogy.

Other characteristics of this type include relatively fine matrix textures (Figure 5) and low clast contents (Figure 6). Striated and faceted clasts are abundant and local lithologies dominate. Pebble fabrics are unimodal, and exhibit moderately strong preferred trends that lie parallel to the inferred direction of ice movement and have slight upvalley plunges (Figure 15b). Three dimensional orientation diagrams from diamictons of type 3 (Figure 17b) are similar to those of type 2 (Figure 17a). Type 3 usually conformably overlies type 1 or type 2. Lower contacts are usually gradational.

Banding in the diamictons is commonly obscured by weathering and groundwater staining indicating that diamictons of this type are probably much more common than field data suggests. Apparently massive tills (type 1) should be examined carefully in the field under both wet and dry conditions, if possible, to determine if banding is present.

Interpretation

Banded or stratified tills have been recently discussed by numerous authors (Boulton, 1976; Dreimanis, 1976, 1982b; Shaw, 1979, 1983; Lawson, 1979a, 1981a; Gibbard, 1980; Haldorsen and Shaw, 1982; Kulig, 1985; and Proudfoot, 1985). Striated and faceted clasts are common in these tills and pebble fabrics often showed a consistent preferred orientation, generally parallel, or sometimes perpendicular, to the direction of former ice flow. Most authors have suggested that one possible origin for stratification in the tills was some form of meltout of ice layers containing varying concentrations of debris, although other plausible mechanisms were also postulated. In general, most of the interpretations made regarding a possible meltout origin were speculative and somewhat controversial (Haldorsen and Shaw, 1982).

Figure 16: Matrix Grain Size Distribution of Bands in Type 3 Diamictons

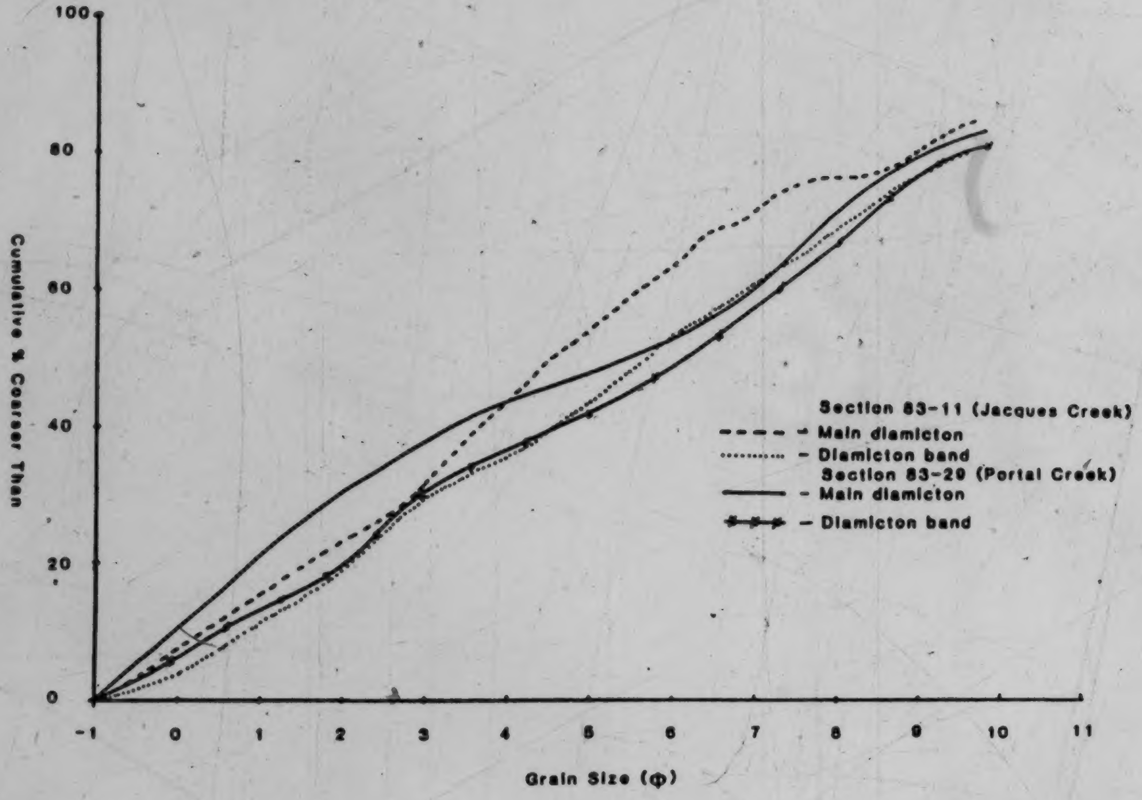
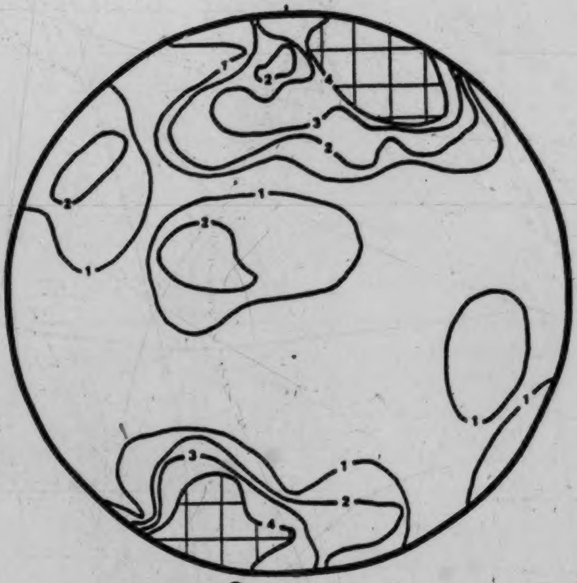


Figure 17: Three dimensional representation of pebble orientations in; a) type 2 diamictons, and b) type 3 diamictons in the Jacques Creek valley (Section 83-11). T and P give the trend and plunge of the principle eigenvector V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured. (Equal-area projection; contours represent number of points in 4% area of hemisphere).

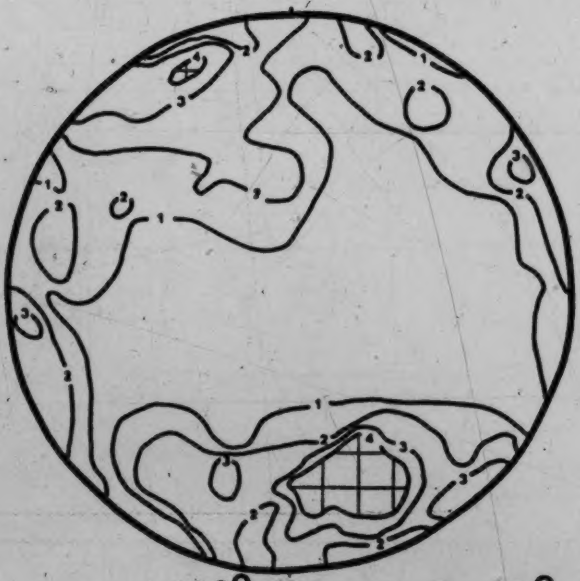
A



T = 9.6° P = 11.5°

S_1 = .64 N = 25

B



T = 162° P = 2°

S_1 = .57 N = 25

Stratification in many of the tills was due to the presence of layers of sorted material. Diamictons with this type of stratification can be deposited as true meltout tills with sorting resulting from flowing water derived from debris poor ice layers (Dreimanis, 1976; Shaw, 1977, 1979) or by a variety of other mechanisms including subaerial sediment flow and overland sheet wash (Lawson, 1979a, 1981a), and basal melting and quiet water sedimentation in water filled cavities beneath floating ice (Gibbard, 1980; Dreimanis, 1982b).

In contrast, diamictons with stratification resulting solely from debris banding have mainly been interpreted as basal meltout tills (Lawson, 1979a, 1981a; Haldorsen and Shaw, 1982). Although debris banding in tills may be produced by mechanisms other than basal melting, the absence of sorted and stratified materials largely restricts other possible origins. For example, the absence of sorted materials between a series of subaerial debris flows would be possible but highly unlikely, especially in the marginal zones of a glacier where meltwaters are abundant. Lawson (1979a) found that a layer of thinly laminated silt and sand commonly separated individual subaerial flow deposits and, in fact, was critical for their recognition in the sedimentary record. He did not observe sorted laminae forming as the result of melting of debris poor layers of basal ice and therefore such laminae should not be used as a property required for the recognition of meltout till. Much of the recent controversy regarding the recognition of meltout till (Lawson, 1981a; Haldorsen and Shaw, 1982; Kulig, 1985) would be clarified if a distinction between sorted and unsorted layers within the stratified diamictons was made.

For this reason banded diamictons which contained sorted and stratified layers were not included in the definition of type 3. Diamictons of this nature would have been identified as type 5, 6, 7, or 8 depending on the thickness and texture of the sorted materials and on the type of stratification. The bands in type 3 are not comprised of well sorted materials and do not exhibit any internal sedimentary structures (bedding) as would be expected if they were "fluvial" in origin.

Lawson (1981a) found that the basal zone of the Matanuska Glacierwas stratified due to alternating debris rich and debris poor layers of ice. Meltout of these stratified zones produced three typical varieties of meltout till:

1. structureless (massive) diamicton,

2. diamicton with discontinous laminae and lenses of sorted and stratified sediment, and
3. diamicton with distinct bands or layers of variable texture, composition or color which may appear draped over large clasts.

Pebbles were oriented parallel to ice flow direction in all three varieties. Contacts between debris bands were gradational and usually had a near horizontal orientation. Shaw (1983) also interpreted the draping of large clasts by diamicton as the product of the meltout of ice from a debris rich layer at the base of a glacier.

The obvious similarities of the banded diamicton in this study with Lawson's banded or layered variety of meltout till (number 3 above) suggests a similar origin for both. Consequently diamictons of type 3 are interpreted as basal meltout tills. The apparent stratification is believed to be the inherited product of debris banding in the base of a glacier, preserved during the meltout process as described by Lawson (1979a, 1981a). The uniform draping of boulders by debris bands is attributed to differential subsidence caused by meltout of the ice adjacent to the boulders as documented by Shaw (1983). A basal origin is indicated by the fine textures, abundance of striated and faceted clasts, the dominance of clasts of local lithology, and the common association of this type with type 1.

This interpretation is supported by pebble fabrics from this type which show pebble orientations parallel to the direction of ice flow with low dips (Figure 15b). Fabrics of this nature were described as characteristic of ancient meltout tills by Harrison (1957), Elson (1961), Lindsay (1970), Dreimanis (1976), Boulton (1976), Lawson (1979a, 1981a), Shaw (1979, 1982, 1983), and Haldorsen and Shaw (1982). The shallow upvalley dip of pebbles and moderate strength of the preferred a-axis orientation were observed in meltout tills at present day glaciers by Boulton (1971) and Lawson (1979a, 1979b and 1981a). The increased scatter of pebbles and lower dips in meltout tills compared to those in basal ice were attributed by these authors to settling and slight lateral shifting during the meltout process. The strengths of preferred pebble orientations (S_1 values) are clearly lower in diamictons of this type than in deposits interpreted as basal tills (eg. types 1 and 2), and generally higher than in other types not believed to be basal tills (Figure 8).

A basal meltout origin for this type is further indicated by its frequent association with type 2 which is interpreted as the lodgement product of actively overriding debris laden ice. Once the deposition of till type 2 by lodgement ceased, debris rich ice probably still occupied the site and subsequent meltout would produce the banded diamicton of type 3 which commonly overlies type 2. Elson (1961) noted that meltout tills were frequently underlain by striated boulder pavements indicating the presence of active debris laden ice prior to the deposition of the meltout till.

E. Type 4: Massive diamicton containing sand and gravel lenses circular in cross-section

Description

Type 4 consists of massive diamictons containing sand and/or gravel lenses which are usually approximately circular in cross-section and generally about one to three meters in diameter (Plate 4). This type was observed only at five localities and was studied in detail only at two, Jacques Creek (Appendix 1) and Portal Creek (Appendix 1). At all localities this type was underlain by a dense, massive diamicton containing abundant striated clasts (type 1) and it usually was vertically gradational with banded diamicton (type 3).

The sorted materials within the lenses may or may not exhibit primary stratification but in all cases deformation is apparent. Normal faults are common. Lenses containing mainly sands usually show little internal structure and often have an irregular contact with the encasing diamicton (Plate 4b). Gravel lenses tend to be less deformed. Individual sand and gravel beds within the lenses are poorly sorted, deformed, faulted, and often contain inclusions of diamicton. Large changes in grain size distribution occur between adjacent beds and even within individual beds over short distances. Large pebbles and cobbles commonly occur within finer grained gravel and sand matrices. Large clasts frequently protrude into the sorted materials along the upper contacts of the lenses (Plate 4c).

There is a continuous gradation between sand and gravel lenses which have nearly perfect circular cross-sections and those that are more irregular in shape. Beds within the latter often dip at high angles. All sand and gravel lenses associated with this type are entirely encased within diamicton which is generally massive and similar in texture to diamictons of type 1 (Figures 5 and 6). Striated clasts of local lithology are common.

Plate 4a: Circular sand and / or gravel lens on vertical section (arrow points to lens).

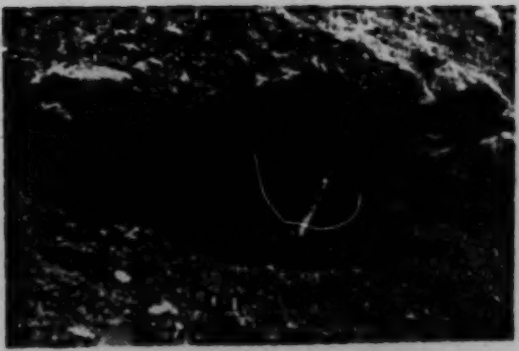
Plate 4b: Circular sand lens (S) in diamicton type 4 (Dm).

Plate 4c: Circular gravel lens (G) in diamicton type 4 (Dm).

A

B

C



Pebble fabric diagrams for type 4 show moderately to poorly developed preferred orientations of the long axes of elongated clasts (Table 2) which generally lie parallel to the direction of ice flow (Figure 18). Although a primary mode is apparent on fabric diagrams, secondary modes are also present (Figure 18a) and clast orientations are relatively scattered (Figure 18b) compared to types 1 and 3. This type usually has a gradational lower contact and often conformably overlies type 1.

Interpretation

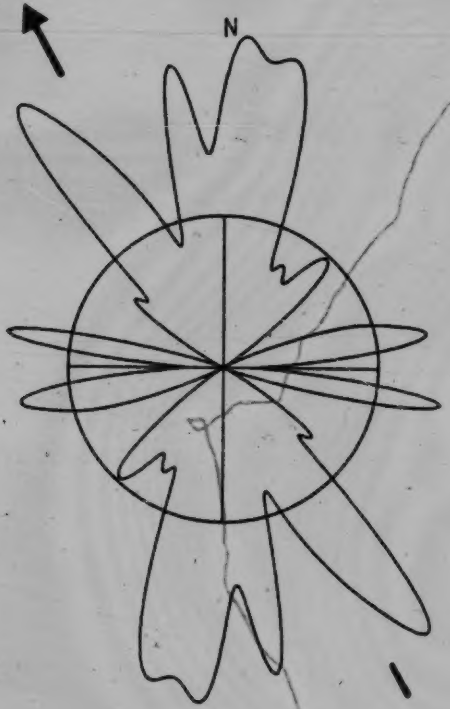
Diamictons of this type are interpreted as tills formed by meltout of basal debris from positions entirely encased within ice. The circular cross-sections of sand and gravel lenses associated with this type, in particular the convex upper surfaces, are believed to be a result of their englacial origin. Meltwaters in englacial stream tunnels near the base of temperate glaciers flow under hydrostatic pressure forming cylindrical tunnels which are circular in cross-section (Nye, 1965). When bedload deposition fills the channels, tube-like deposits of sand and gravel (circular or nearly circular in cross-section) develop. Such deposition may occur during waning flows prior to the abandonment of the tunnel. Channel abandonment would be common during the late stages of deglaciation, when the chances for the preservation of the tunnel deposits in the sedimentary record would be high.

Deposition within the tunnels by flowing water would be accompanied by the addition of clasts and debris from the eroding ice surfaces above and adjacent to the channel. Pieces of debris rich ice may break off the adjacent ice surface and subsequently be buried by sediment. This would explain the presence of large clasts and blocks of diamicton within the sorted materials. During meltout of the underlying ice settling would result in deformation and normal faulting of the strata. Deformed and faulted statification and beds lying at high angles indicate extensive post-depositional movement.

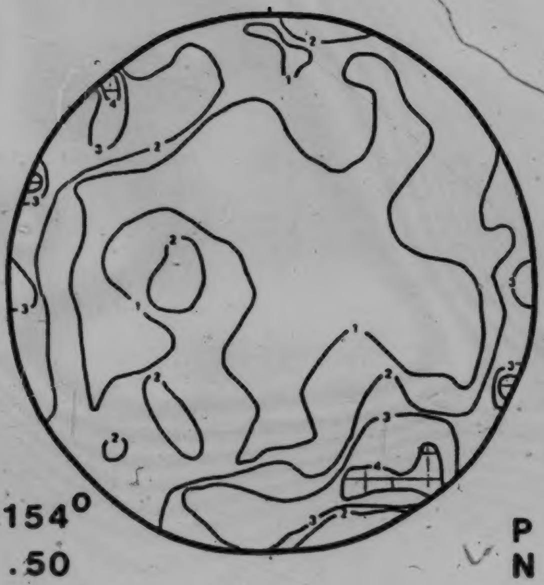
Preservation of the circular cross-section of the sorted lenses during meltout requires debris-rich ice. Debris concentrations up to 80% by volume have been observed at the base of some temperate glaciers (Boulton, 1968, 1975). Debris concentrations of this magnitude would allow for the preservation of the circular cross-sections of the sand and gravel lenses if they originally formed near the base of the glacier, allowing for minimal post-depositional disturbance. Since persistent englacial streams are concentrated

Figure 18: a) Rose diagram representing two dimensional pebble orientations in diamicton of type 4 (N=25). b) Three dimensional representation of pebble orientations in type 4 diamictons; Sample locality in the Rocky River Valley (Section 83-5); Arrows point downvalley; T and P give the trend and plunge of the principle eigenvector, V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured. (Equal-area projection; contours represent number of points in 4% area of hemisphere.)

A SECTION 83-5 UNIT 3A ROCKY RIVER N = 25



B



T = 154°
S_1 = .50

P = 7.6°
N = 25

in the basal portions of glacier toes, the possibility for the formation and preservation of englacial tunnel deposits is greatly increased in that zone. The more irregular and disrupted lenses probably were deposited in tunnels which overlay thick, or debris poor, layers of ice. This would allow for substantial differential settling and thus account for the irregular shape and orientation of the lenses.

The protrusion of large clasts into the upper part of the sandy lenses from the overlying diamicton, suggests that the sands were deposited englacially. Clasts frozen into the glacier would occasionally protrude into englacial cavities and deposition around them would eventually occur. Once meltout was complete, these clasts would be partially encased in both diamicton and sorted materials.

The fine matrix textures and common presence of striated clasts of local lithology indicate that this type was basally derived. The preferred orientation of the a-axis of pebbles, parallel to the valley walls, probably reflects the direction of moving ice. The high scatter of pebble orientations compared to basal tills may be the result of meltout of greater volumes of ice from the englacial position of formation.

Type 4 is associated with banded diamictons (type 3) which are also interpreted as meltout tills. In addition, this type commonly conformably overlies type 1 which is interpreted as basal till. Since englacial tills would normally be expected to overlie basal tills, the observed and expected sequences are the same.

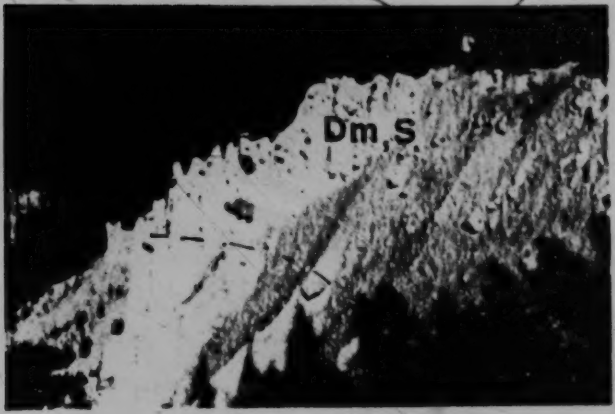
F. Type 5: Bouldery diamicton with numerous, highly disturbed, sand and gravel lenses and layers

Description

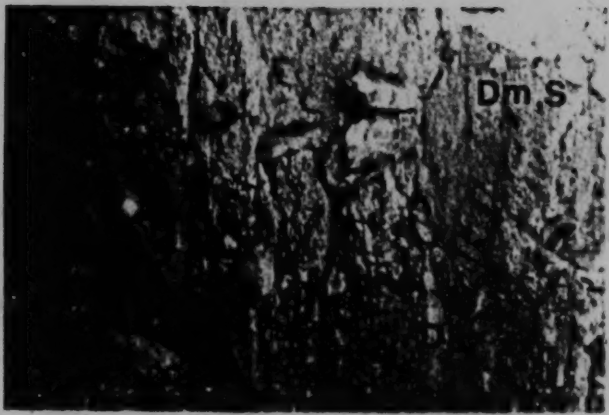
Bouldery diamicton with highly disturbed lenses and beds of sand and gravel is relatively common in the Jasper area, particularly at or near the surface. Boulders generally constitute at least 10-20% of the deposits (Plate 5). Clasts are dominantly subangular and non-local lithologies are common. Far travelled erratics, specifically talcose and garnetiferous schists of the Athabasca Valley Erratics Train derived from west of the Continental Divide (Roed, et. al., 1967) frequently occur in the upper parts of exposures of of this diamicton. In addition, lithological analyses indicate that many clasts were derived

Plate 5: Type 5 diamicton (Dm,S) gradationally overlying finer textured massive diamicton of type 1 (Dm); note the higher boulder content of type 5 diamicton (Plate 5a) and lighter color due to greater sand content (Plate 5b).

A



B



from bedrock formations that outcrop mainly at high elevations in upvalley areas. Striated clasts are uncommon. Diamictons of this type are massive to weakly stratified and generally matrix-supported. They range from 2-20 meters in thickness and modally are about 5m thick. They usually have matrix textures which vary from silty sand to sandy mud (Figure 5).

Diamictons of type 5 may be massive and unoriented or weakly stratified. Crude horizontal layering is often apparent due largely to variations in clast size, some layers being relatively rich in boulders and cobbles. Large clasts are commonly concentrated at the base of this type (Plate 5b). Sediments are poorly compacted and cemented and consequently, exposures of this type are susceptible to slumping (Plate 5a).

Poorly to moderately sorted sands and gravels occur sporadically as poorly defined lenses and layers throughout the diamicton. Contacts between sorted and unsorted materials are often highly irregular and locally appear normally faulted. The lenses usually have planar upper surfaces and trough-shaped lower surfaces. Stratification is rarely preserved in the lenses.

Pebble fabric diagrams for diamictons of this type are bimodal or multimodal (Figure 19). They exhibit a relatively high degree of scatter but still have significant preferred orientations which are usually parallel, but may also occur at angles of up to about 20° to the valley orientation (Table 2). A-axis dips are generally high (Figure 20).

The lower contact of type 5 is usually gradational (Plate 5) but locally is well defined and planar. This type generally overlies thick, massive diamictons of type 1. Type 5 is also commonly vertically and laterally associated with better sorted and stratified deposits of diamicton type 6 which show little or no disruption.

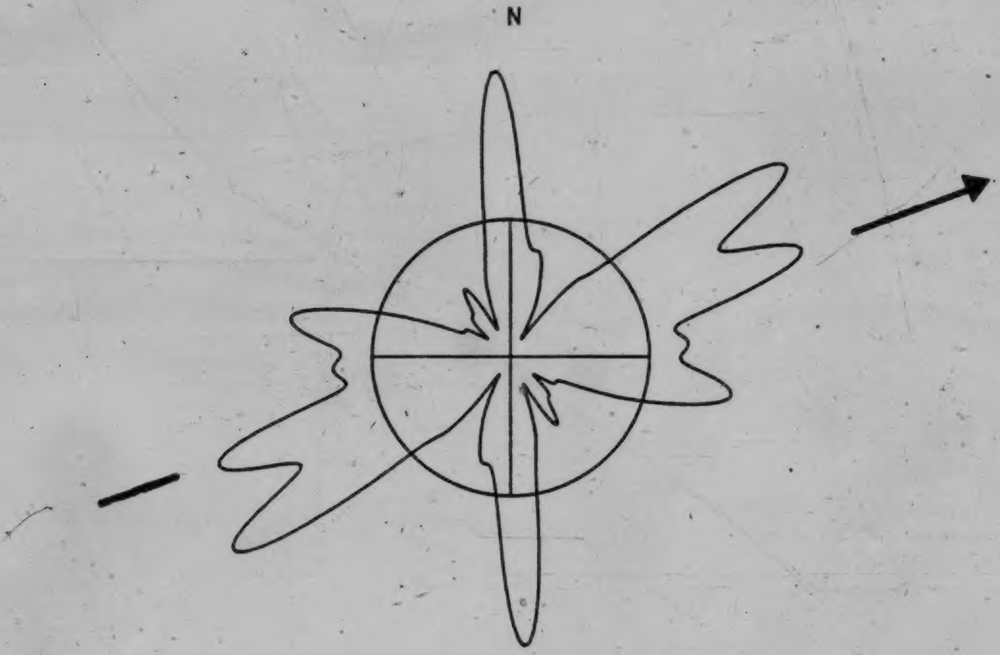
Interpretation

Diamictons of type 5 are interpreted as supraglacial debris flow deposits. Sands and gravels associated with the diamictons are interpreted as the deposits of supraglacial streams. A supraglacial origin for the debris comprising this type is supported by the abundance of large clasts, rarity of striated clasts, high clast angularity, dominance of clasts derived from formations outcropping only at high elevations, and the large percentages of clasts of non-local lithology. Similar characteristics have been described

Figure 19: Rose diagrams representing two dimensional pebble orientations in diamictons of type 5 (N=50). a) Portal Creek valley (Section 83-29); b) Astoria River Valley (Section 83-27); Arrows point downvalley.

A SMOOTHED ROSE DIAGRAM. K = 200 N = 50

SECTION 83-29 UNIT 5 PORTAL CR



B SECTION 83-27 UNIT 1 ASTORIA R

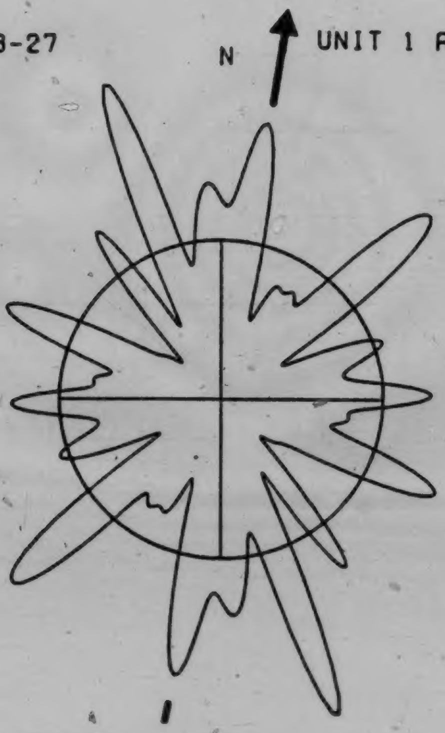
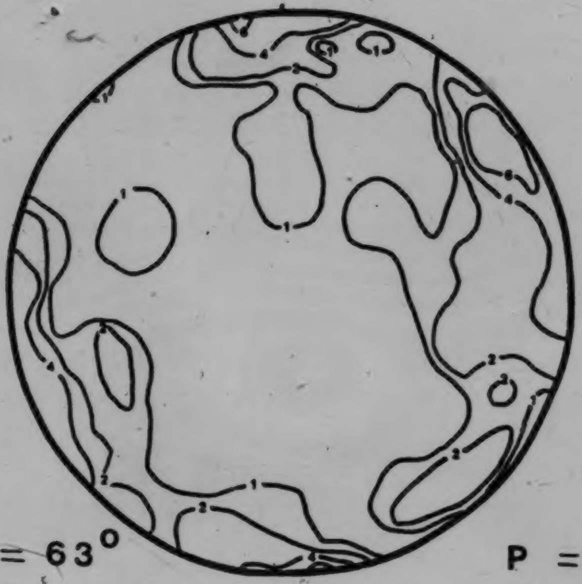


Figure 20: Three dimensional representation of pebble orientations in type 5 diamictons. a) Portal Creek Valley (Section 83-29); b) Astoria River Valley (Section 83-29). T and P give the trend and plunge of the principle eigenvector, V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured. (Equal-area projection; contours represent number of points in 2% area of hemisphere).

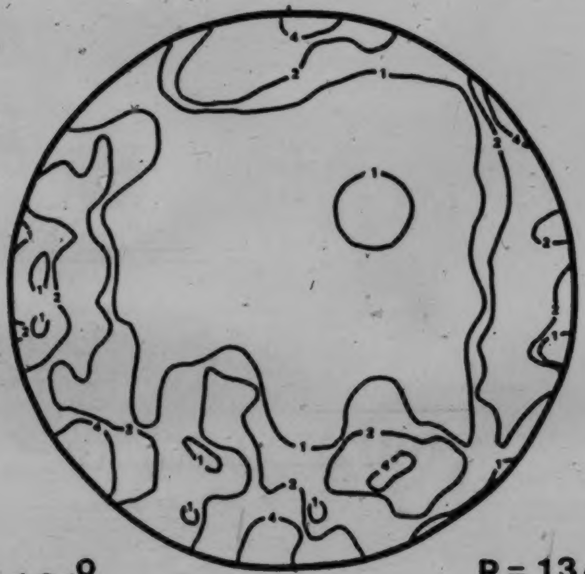
a



T = 63°
S_1 = .56

P = 7.2°
N = 50

b



T = 181°
S_1 = .47

P = 13.4°
N = 50

for supraglacial tills by numerous authors (Sharp, 1949; Elson, 1961; Drake, 1971; Flint, 1971; Goldthwait, 1971; Stewart and MacClintock, 1971; Shilts, 1973 and 1976; Dreimanis, 1976; Boulton and Eyles, 1979; Eyles, 1979; and Lawson, 1979a, 1981a, 1981b). Supraglacial debris originates mainly as rockfalls, avalanches and debris flows from nunatuks and valley sides (Boulton and Eyles, 1979 and Boulton, 1975).

Horizontally continous units of clast-poor diamicton overlying relatively clast-rich layers have been observed in modern supraglacial sediment flows (Lawson, 1981a). Variations in clast size distribution develop from localized liquifaction or other processes causing clast settlement during flow or deposition (Lawson, 1981a, p.83). Concentrations of clasts in poorly defined horizontal layers may also be the result of winnowing of fines by meltwaters. Lawson (1979a) found that vertical and horizontal changes in clast concentrations were due to periodic and spatial variations in meltwater flow. Debris released from ice by ablation processes on low angle slopes, was rapidly coarsened by meltwaters. Gravel lags were frequently formed and sometimes covered and preserved beneath sediment flow deposits.

Massive diamictons without preserved sand and gravel lenses were commonly observed on the Matanuska Glacier by Lawson (1979a, 1981a). These diamictons were often underlain by large volumes of ice prior to their final deposition. Consequently they underwent significantly more resedimentation during the final stages of till formation resulting in total reworking of the source materials and destruction of their original properties (Lawson, 1981a). Such resedimentation may be the result of either dynamic ablational slope processes such as spalling, rolling and sliding of debris down steep ice surfaces or more passive movements such as sediment flow and sheet flow on gentle slopes. The resulting structureless deposits have been termed "ice slope colluvium" by Lawson (1981a). As the texture of ablation deposits coarsens with increased resedimentation and fluvial reworking, and as the amount of reworking would naturally be highly variable, the texture of supraglacial ablation deposits should also be highly variable (Dreimanis, 1976).

The texturally heterogeneous, poorly sorted deposits observed by Lawson (1979a) as the products of ablation processes on the Matanuska Glacier are similar in several ways to diamictons of type 5. Lenses of sorted materials formed by glacial meltwaters commonly occurred with the ablation deposits. Diamictons were frequently structureless with the exception of a weak long axis alignment of pebbles. The preferred orientation showed no relationship to ice flow direction, being mainly a function of the trend of ice ridges on the surface of the ablating glacier. The degree of scatter of measured axes about the mean in Lawson's study (S_1=0.550 to 0.638) is comparable to that obtained on diamictons of type 5 S_1=0.472 to 0.615)(Table 2). Similarily the variable and generally high dips of pebbles in this type are comparable to those obtained by Lawson (1979b, 1982) in ablation deposits. Dips in the latter varied from near vertical to horizontal.

The absence of stratification within sorted materials associated with this till type and apparent normal faulting of lenses indicates disruption and differential settling due to melting of the underlying ice. However, since the sorted materials have maintained an overall horizontal orientation and some sand lenses are intact, little ice probably was underlying these sediments during their last stage of formation. The amount of preservation of sedimentary structures in supraglacial tills is largely determined by the amount and rate of differential melting of the underlying ice that occurs subsequent to the last sedimentation event during till formation.

As a result of ablational slope processes the entire supraglacial complex may have been mobilized and redeposited a number of times. Crude horizontal layering within diamictons of this type, as a result of variations in clast size, may be the result of stacking of individual debris flows. This is consistent with the wide range of textures exhibited by diamictons of this type and further suggests a supraglacial origin for them.

The metamorphic erratics of the Athabasca Valley Erratics Train, commonly found in diamictons of type 5, most likely were carried in a supraglacial position (Roed et. al., 1967). These rocks are soft and easily disaggregated due to their well developed schistosity and, therefore, it is unlikely that they could have survived basal transport for any significant distance. Kruger (1979) noted that the preservation of friable clasts and sand lenses in tills precluded an origin by lodgement. The nearest outcrop to Jasper of rocks similar to those in the Athabasca Valley Erratics Train is more than 50 km to the west. Clasts of this type could not have maintained their high angularity during basal transport over such large distances. The frequent association of these erratics with type 5 therefore suggests that it is supraglacial in origin.

There is evidence, however, that some of the debris comprising this type may have been derived subglacially. The presence of occasional, albeit rare, striated clasts, relatively fine grained textures and low clast contents in some diamictons, all suggest a local subglacial origin.

Deposits of this type are often laterally and vertically gradational with deposits of type 6, interpreted as proglacial debris flow deposits. This lateral change between supraglacial and proglacial deposits would be expected in ice marginal areas. A vertical gradation between these two types is also likely to occur due to two factors:

1. As a glacier down-wastes in its ablation zone, progressively larger volumes of subglacially derived debris would be released on the surface and incorporated into the supraglacial deposits thus resulting in a downward vertical gradation from entirely supraglacially derived debris to dominantly subglacially derived debris; and
2. Once finally deposited, supraglacial tills may be covered by debris flows from adjacent ice surfaces that are topographically higher.

G. Type 6: Massive to moderately stratified diamicton containing abundant, trough-shaped, sand and gravel lenses

Description

Deposits of type 6 are common in the Jasper region. They consist dominantly of massive, matrix- to clast-supported, diamicton with abundant lenses and thin beds of sorted materials (Plate 6a). Sorted sediments generally comprise 10 to 30% of type 6 although locally they may constitute as much as 40-50% of the deposits. The diamicton usually has a relatively sandy matrix, generally more than 50% sand (Figure 5), but textures can be highly variable over short distances. Irregularly shaped layers of pebbly sand a few centimeters in thickness commonly occur within the diamicton (Plate 6b). Total clast content varies from 20 to 80%. Vertical variability in clast size distribution is locally present giving the diamictons a stratified appearance. Clasts vary in shape from subangular to well rounded with most being subrounded to rounded. Scattered, striated clasts commonly are present. Cementation and compaction are highly variable. Angular inclusions

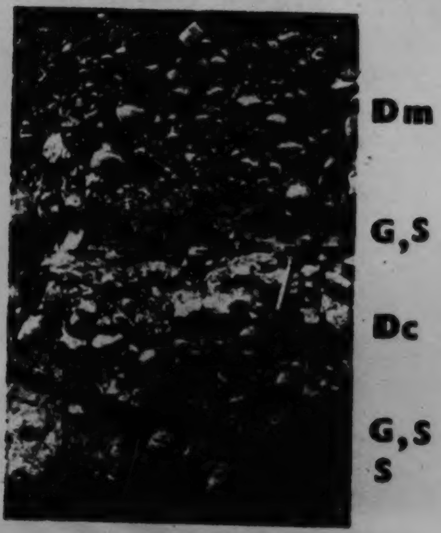
Plate 6a: Type 6 diamicton (Dm) with trough shaped sand lenses (St) overlying horizontally stratified sands (S) and gravels (G).

Plate 6b: Thin layers of gravel and sand (G and S) in clast-supported, (Dc), and matrix-supported, (Dm), diamicton of type 6.

Plate 6c: Deformed (d), faulted (sheared?) (s) and folded (f) sands (S) and gravels (G) in the upper part of a diamicton (Dm) of subtype 6a.

A

B



C

of underlying materials are common in the lower portions of diamicton beds of type 6.

Stratification within the diamictons may be poorly to moderately developed, as a result of changes in the grain size distribution of the matrix and clasts. This stratification is accentuated by the ubiquitous presence of thin beds and lenses of sand and gravel (Plate 6a). Laminated silts and clays also occur locally within the diamictons.

Beds of sand and gravel are generally near horizontal, although downvalley dips up to 10° were measured on some strata. Although most beds are very thin (1-5 cm) they are usually laterally extensive, sometimes being traceable along outcrops for several meters. The upper and lower contacts of sorted beds are usually diffuse, especially when the beds are thin.

Most sand and gravel lenses are one to five meters wide and 0.5 to one meter thick. They generally have planar upper surfaces and concave lower surfaces (plano-concave geometry). Contacts with surrounding sediments vary from sharp to gradational. Sedimentary structures within the lenses include trough crossbedding and smaller scale horizontal laminae and planar cross-beds. Trough cross-beds often are conformable with the lower boundaries of the lenses. Most beds are moderately to well sorted.

Pebble fabric diagrams for type 6 usually are multimodal and exhibit weakly developed preferred orientations which may be either parallel or perpendicular to the former direction of ice flow (Figures 21 and 22). In general, S_1 values for pebble fabrics from type 6 are lower than for any of the other type studied (Figure 8 and Table 2).

The lower contact of this type varies from sharp to gradational and frequently appears erosive. At section 82-33 (Appendix 1) "scour troughs", one to five meters wide and one half to one meter deep, have truncated bedding in the underlying sands (Plate 6a). This type may overlie glacial or non-glacial deposits. It frequently is laterally and/or vertically associated with type 5 and commonly is overlain by type 1. Sand lenses in the upper part of diamictons of this type are commonly deformed when the overlying deposits are diamictons of type 1 (Plate 6c).

Two subtypes are defined, based on the relative abundance of diamicton and on the amount of deformation of the associated stratified materials.

Subtype 6a

Subtype 6a consists of intercalated diamicton, sands and gravels (Plate 7a). Diamicton beds dominate this type but they are rarely more than one or two meters in thickness. Sorted materials generally comprise approximately 10 to 20% of this subtype. They occur as irregularly shaped, poorly defined layers. Although these sand and gravel layers are indistinct, they usually show a near horizontal orientation and general lensoid shape. Primary stratification is apparent but is often deformed. The amount of deformation is usually greatest in the upper part of this subtype. Sand layers near the upper contact may be faulted, folded and/or sheared (Plate 6c). Deformation is usually compressive. Load structures and injections may also be common on the upper and lower surfaces of silt and sand beds (Plate 7b). Sorting may be quite poor with large pebbles and cobbles occuring within sand and silt beds. Large clasts at the base of diamicton beds occasionally deform bedding in underlying sands or silts. Folded laminae are locally present. This type is commonly overlain by massive diamictons of type 1 or 2 (Plate 7c).

Pebble fabric diagrams for subtype 6a (Figure 21) are multimodal and exhibit weakly developed preferred orientations (Table 2). The latter may be either parallel or perpendicular to the former direction of ice flow. Rose diagrams for subtype 6a in some cases exhibit 2 or 3 modes of similar orientations (Figure 21b) resulting in higher S1 values than typical of type 6 (see Triangle on Figure 8). Relatively low a-axis dips of elongated pebbles are characteristic of subtype 6a (Figure 22b).

Subtype 6b

In subtype 6b, little or no faulting or deformation of stratified materials associated with the diamictons is apparent and the proportion of diamicton compared to subtype 6a is generally low (Plate 7c). Sand and gravel lenses are abundant (usually comprising 25-50% of the deposits), relatively well defined, and typically plano-concave in cross-section. Subtype 6b is generally sandier than subtype 6a (Figures 5 and 6).

Pebble fabric diagrams for subtype 6b (Figures 21c and 22c). usually are multimodal and exhibit weakly developed preferred orientations (Table 2). The latter are often parallel to the former direction of ice flow. Three dimensional analyses of pebble orientations indicate that the long axes of pebbles in subtype 6b preferentially dip up

Plate 7a: Intercalated diamicton (Dm) and gravels (G) - subtype 6a.

Plate 7b: Folded (f) and deformed (d) bedding in a sand and silt lens (S) within subtype 6a diamicton; note the injection structure adjacent to the knife.

Plate 7c: Interbedded diamicton (D), sand (S) and gravel (G) (type 6) overlain by massive diamicton of type 1 (Dm). Undeformed sands and gravels dominate over diamicton in the bottom part of the photo (subtype 6b) and grade upward into deformed beds with a progressively greater proportion of diamicton (subtype 6a).

A

B

C

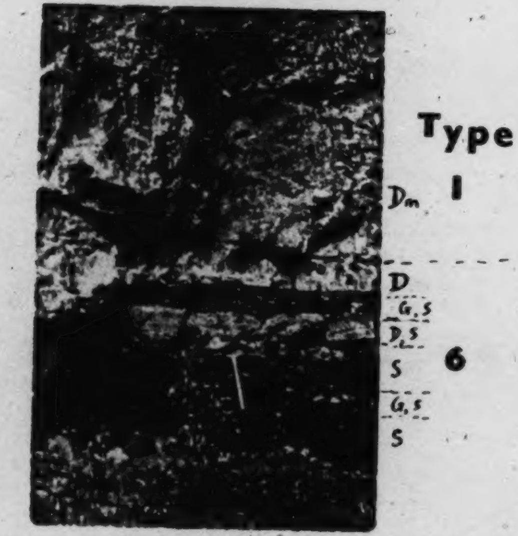
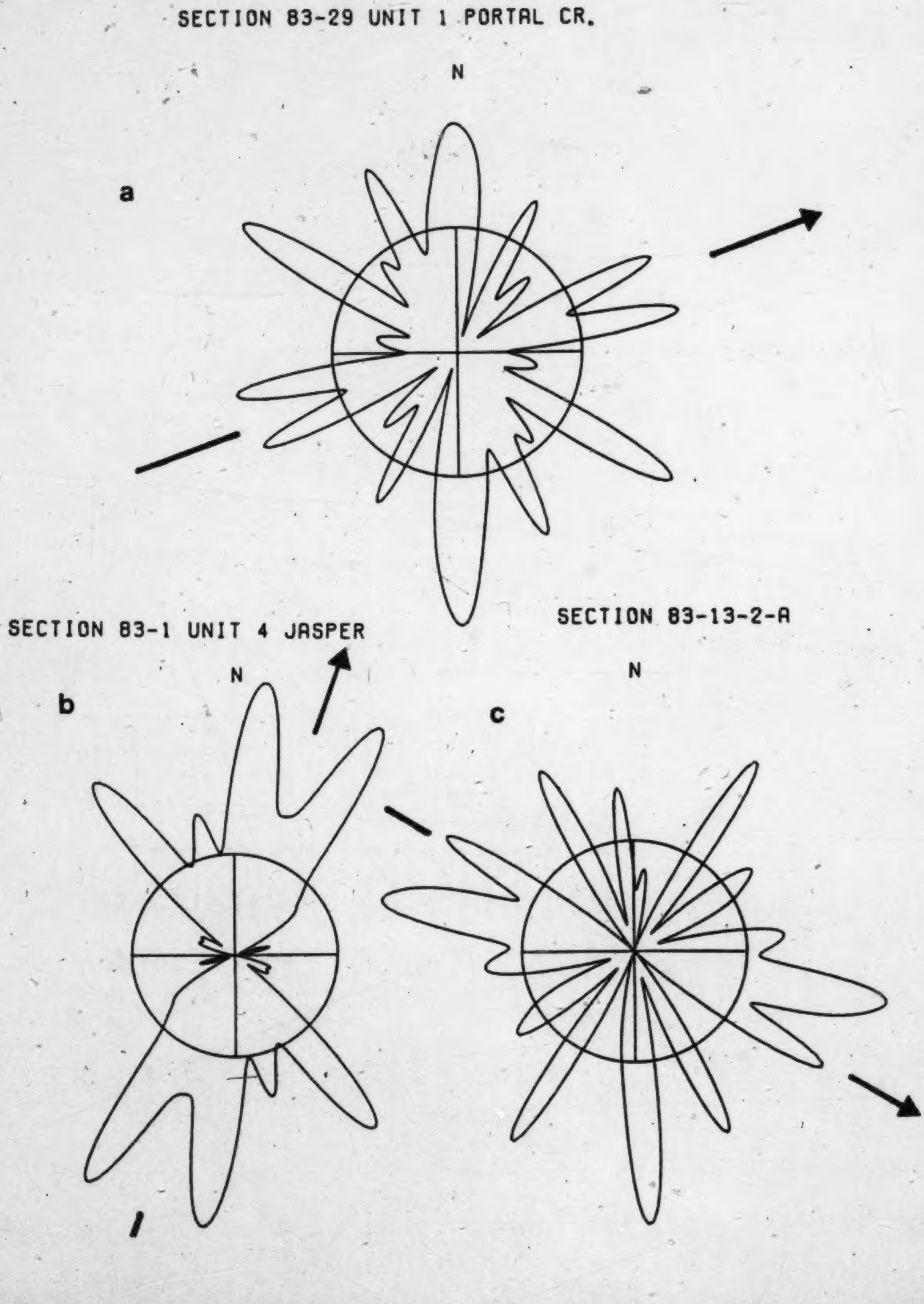


Figure 21: a) Rose diagram representing two dimensional pebble orientations in diamicton of type 6 (N=50)in the Portal Creek Valley (Section 83-29). b) Rose diagram representing two dimensional pebble orientations in diamicton of type 6a (N=50) in the Jasper townsite area (Section 83-1). c) Rose diagram representing two dimensional pebble orientations in diamicton of type 6b (N=25) in the Snake Indian River valley (Section 83-13). Arrows point downvalley.


SECTION 83-29 UNIT 1 PORTAL CR.
N
a
SECTION 83-1 UNIT 4 JASPER
N
b
SECTION 83-13-2-A
N
c

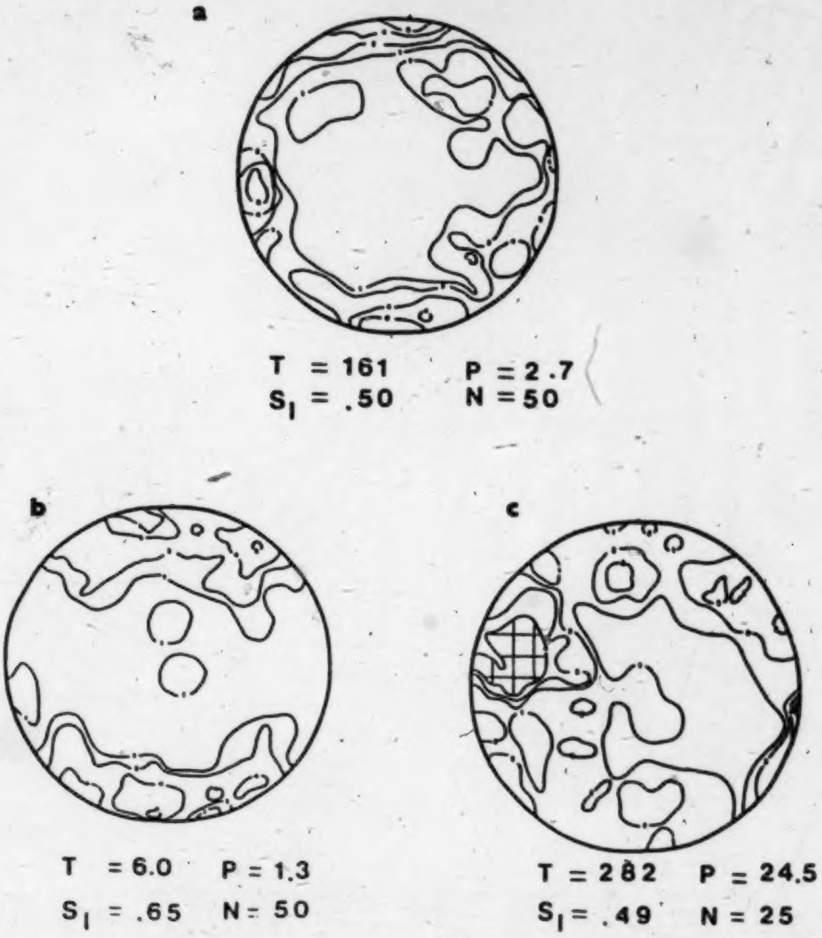


Figure 22: a) Three dimensional representation of pebble orientations in type 6 diamicton in the Portal Creek valley (Section 83-29); (Equal-area projection; contours represent number of points in 2% area of hemisphere.) b) Three dimensional representation of pebble orientations in type 6a diamicton in the Jasper townsite area (Section 83-1); (Equal-area projection; contours represent number of points in 2% area of hemisphere.) c) Three dimensional representation of pebble orientations in type 6b diamicton in the Snake Indian River Valley (Section 83-13); (Equal-area projection; contours represent number of points in 4% area of hemisphere.) T and P give the trend and plunge of the principle eigenvector, V_1; S_1 gives the strength of clustering around V_1; N is the number of clasts measured.

valley at relatively high angles (Figure 22c).

Subtype 6b occurs commonly on the surface in the Jasper region. In the subsurface this subtype is often conformably overlain by subtype 6a which is in turn generally overlain by till types 1 or 2.

Interpretation

Type 6

Sediments of type 6 are believed to have been deposited in the proglacial environment. Diamictons are interpreted as the deposits of mass movements emanating from the glacier terminus region. The presence of structures interpreted as flow folds, abundant load structures, locally erosive lower contacts and clasts which deform underlying beds supports a debris flow origin for the diamictons.

Lenses of sorted materials were likely deposited in proglacial stream channels which developed on the surface of previously deposited sediments. This interpretation is based on the plano-concave geometry of the lenses, the absence of faulting and deformation (indicating deposition over ice free sediments) and the presence of bedding and laminae which conform to the trough shaped floor of the lenses. The latter are very similar to channel fill structures observed in many subaerial streams (Reineck and Singh, 1980). As surface stream channels became blocked or buried by subsequent flows, new channels formed elsewhere. This explains the random distribution of sand and gravel lenses throughout this type. Thin beds of stratified sand and silt were likely deposited by glacial meltwater flowing in sheets after deposition of underlying debris flows (Lawson, 1979a). The presence of laminated silts and clays indicate local ponding also occurred between flow events.

The presence of beds and lenses of sorted materials is critical to the genetic interpretation of the encasing diamictons. Stratigraphic relationships sometimes clearly indicate that diamictons overlying and underlying sorted materials were deposited at different times. In adjacent areas, these diamictons are often indistinguishable and contacts between them cannot be recognized. Thus, due to similarities in composition, a series of overlapping debris flows may only be recognized as different events by the presence of these intervening stratified materials. Lawson (1981a) found that most sediment flows at the margin of the Matanuska Glacier were accompanied by meltwater flowing over their surfaces. He stated that

> "a top layer of thinly laminated silt and sand is generally critical to identifying individual flow deposits in depositional sequences"

(Lawson, 1981a, p80).

Multiple superimposed flows may locally be recognized by layering within the diamictons themselves. Changes in total clast content and grain size distribution between layers could reflect different sediment sources, modes of transport, and variations in the amount of reworking of the deposits prior to final deposition. The high abundance of rounded clasts and rarity of striations in some beds suggests a greater degree of reworking of the sediments prior to final deposition compared to deposits which, otherwise, are texturally and compositionally similar.

Significant changes in matrix texture over short vertical and horizontal distances (in the order of centimeters) within diamicton beds, may be the result of the erosion and incorporation of materials in the path of the debris flows. Lawson (1981a)found that the bulk of debris flows near Matanuska Glacier were composed of massive diamictons which locally contained inclusions of texturally or structurally distinct sediment. Angular inclusions of underlying materials within the lower portions of some type 6 diamictons are interpreted as rip-up clasts. The presence of these rip-up clasts and the sometimes 'scoured' lower contact of the diamictons, indicates that the flows were at least locally erosive.

The multimodal, weakly developed pebble fabrics characteristic of type 6 are typical of debris flow deposits (Marcussen, 1975, Lawson, 1979b, 1982).

Diamictons of type 6 are believed to have originated from basally transported debris, subsequently exposed at the glacier margin or surface. The similarity of some diamictons of this type to the basal tills of type 1 (i.e. abundance of striated clasts, low total clast contents, and clay / silt-rich matrices) supports this interpretation. The abundance of clasts of local lithologies and conspicuous absence of far travelled erratics, particularily of the Athabasca Valley Erratics Train (Roed et. al., 1967) normally found on surface tills in the area, precludes a purely supraglacial origin. The basal debris rich zone is the primary source of proglacial sediment in many modern glaciers (Boulton, 1968, Lawson, 1979a). Undoubtedly some of the debris comprising this type was supraglacially derived but the abundance of local clasts in most deposits suggests that the main source was subglacial.

Where this type was supraglacially derived it would be indistinguishable from deposits of type 5 in the absence of normal faulted sand lenses and high boulder contents which are common in type 5. The deposits formed by mass movements of debris on a glacier surface (type 5) could be very similar in nature to supraglacially derived debris flows in the proglacial environment (type 6). In addition, types 5 and 6 are frequently vertically and laterally associated, often grading into each other. This would be expected as both types may be deposited in similar environments at or near the ice margin. Gravity flows are common in both environments, the only difference being whether the flows are over glacial ice or previously deposited sediments. If faults and collapse structures are not preserved in supraglacial deposits after the melting of underlying ice (due either to:

1. the absence of structures which would record differential settling, such as sand lenses,
2. slow or spatially homogeneous melting, or
3. the total disaggregation of the sediments during deposition),

then the resultant deposits would be indistinguishable from supraglacially derived debris flows. As a result, it is possible that type 6 locally, also may have been deposited supraglacially.

Subtype 6a

The internal structures of subtype 6a are believed to be the result of the proximity, and in some cases the overriding, of glacial ice. The relative abundance of diamicton, poor sorting, and the presence of large clasts within sand and silt beds suggests a more proximal environment than for subtype 6b. The abundance of compressive deformational features such as faults, folds, and shear structures, indicates possible pushing or overriding by glacial ice. In addition, subtype 6a is usually overlain by deposits interpreted as basal tills (mainly types 1 or 2) suggesting the presence of an overriding glacier.

The stronger S_1 values and lower a-axis dips of clasts, exhibited by subtype 6a pebble fabrics compared to subtype 6b fabrics, may be the result of the nature of more proximal debris flows or of compaction by overriding ice (Lawson, 1979b) The bimodality of some of these fabrics may be due to multiple flows of different source direction or pebble reorientation by overriding ice (MacClintock and Dreimanis, 1964, Ramsden and Westgate, 1971). The latter may also explain the anomalously high S_1 value of a pebble fabric from type 6a at section 82-33 (Appendix 1, Triangle in Figure 8).

The precise location of the depositional site of subtype 6a relative to glacial ice cannot be determined and it is even possible that this subtype was locally deposited in subglacial stream cavities. There is little distinction between deposits in large subglacial stream cavities at the margin of the modern Athabasca Glacier and those immediately in front of the ice. Due to the abundance of crevasses draining supraglacial meltwaters, most streams emanating from the toe of the Athabasca glacier are subglacial. Thus little difference in the overall amount of sorted material along stream channels would be expected between the subglacial region near the ice margin and the immediate proglacial environment. Differences in factors such as fabric strength and abundance of striations would be expected between these two local environments due to the proximity of grounded ice in the former. This would especially be true in the case of ice advancing over non-glacial materials. However, no such differences were observed in this study. More detailed investigations of this subtype may detect such differences and provide more information on the local depositional environment.

Subtype 6b

Deposits of subtype 6b are interpreted as distal proglacial sediments that have been more reworked by fluvial action than the deposits of subtype 6a. The coarser textures, better sorting, relative abundance of sand and gravel lenses, and the lower proportion of diamicton supports this interpretation. The high, preferential upvalley dips of clasts, present only in subtype 6b, may reflect crude imbrication in the deposits. Such imbrication may be the result of the high number of clasts in contact with each other compared to subtype 6a. Imbrication of the a-b plane has been observed in some debris flow deposits (Fisher, 1971; Naylor, 1980).

An alternative interpretation of subtypes 6a and 6b is that they were deposited in laterally equivalent sites along the ice margin. Variations in sorting, texture, and relative abundance of sand, gravel and diamicton may merely be due to differences in the amount of water issuing from different locations along the ice front. However the vertical sequence of till types 1 and 2 over subtype 6a over subtype 6b is very common. This sequence is the same as that expected at the base of an advancing glacier and suggests that subtypes 6a and 6b, respectively represent proximal and distal debris flow deposits. In addition, subtype 6b occurs frequently as the uppermost unit in many exposures in the Jasper region and probably was commonly deposited during ice retreat. The abundance of meltwaters, expected during the retreat stage were probably responsible for the relatively large amount of sorted materials associated with diamictons of subtype 6b.

H. Type 7:Coarse diamicton interbedded with sands and gravels

Description

Type 7

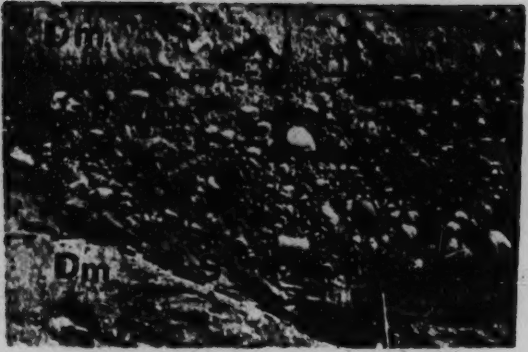
Diamicton beds, generally in the order of 1 to 5 m thick, interbedded with beds of sand and gravel (Plate 8) are common in the Jasper region. Type 7 is similar to type 6 and they are gradational with each other (particularly subtypes 6b and 7a). An arbitrary distinction is that sorted materials clearly dominate over diamicton in type 7, composing more than 50% of the deposits, and the diamictons are more coarse-textured. The thickness of sand and gravel beds associated with this type usually is in the order of meters and they are bounded on their upper and lower surfaces by diamicton. The diamictons usually have a very sandy matrix (Figure 5) and high clast contents (Figure 6). They may be matrix or clast-supported. They generally are poorly to very poorly sorted but grade into moderately sorted gravels (Plate 9a). The latter are often clast-supported, imbricated and stratified. The diamictons vary from massive to moderately stratified, most being weakly stratified. Total clast contents vary from 10-80%, most often being over 50%. Striated clasts are rare but their abundance increases as sorting decreases. Most clasts fall within the pebble or cobble clast size ranges but boulders also occur. Clasts of non-local lithology usually dominate and are angular to rounded with most being subrounded. Clasts of local lithology tend to be more angular. In a few areas where the local bedrock is mainly soft, poorly indurated shales and siltstones (e.g. Pocahontas area), local clasts dominate over those of far travelled lithology. Sorting, stratification, clast roundness, and total clast content covary and appear to decrease upvalley. Average clast

Plate 8a: Horizontally bedded gravels (Gp), trough-cross stratified sands (St) and diamicton (Dm) - type 7a (6b?).

Plate 8b: Clast-supported diamicton (Dc) of subtype 7b interbedded with horizontally stratified sands (Sp) and gravels (G).

Plate 8c: Matrix supported diamicton of subtype 7a (6b?) interbedded with slightly deformed sands, S(d), and gravels, G(d).

A



B

C

Plate 9a: Clast-supported diamicton (Dc) that grades into matrixsupported diamicton (Dm); note the highly irregular contact of the sands (S) with the overlying diamicton - type 7.

Plate 9b: Erosional contact between trough cross-stratified sands (St) and gravels (Gt) and an overlying clast-supported diamicton of type 7 (Dc).

A

B

size generally increases upvalley.

Contacts between diamicton beds and sands and gravels vary from planar and conformable (Plate 8b) or erosional (Plate 9b) to highly irregular (Plate 9a). Contacts are often deformed (Plate 8c). Type 7 was observed mainly in the upper portions of terraces in the Athabasca valley. It commonly grades laterally and vertically into types 6 and 1. Thick sequences of gravel usually underlie or overlie deposits of type 7.

Two subtypes of type 7 can be distinguished. They grade into each other and are defined below as end members of this gradational suite.

Subtype 7a

Subtype 7a is characterized by unsorted to very poorly sorted sandy diamicton interbedded with sands and gravels (Plate 8a). The diamictons are generally matrix-supported, show little or no stratification and contain some striated clasts. Large and rapid, vertical and horizontal, changes in grain size distribution, sorting and bed orientation are common in the sands and gravels (Plate 10a and b). Moderately to poorly sorted gravel beds with clasts up to boulder size are often interbedded with well sorted sands and silts (Plate 10c). Strata commonly exhibit dips in the order of 20° to 40° and they are frequently folded and faulted (Plate 11a). Angular inclusions of texturally distinct material are often present within the deposits (Plate 11b). Deformed (loaded) bedding planes (Plate 8c) and fluid injection structures (Plate 11c) are particularily common. Diamictons of this subtype may occur as horizontal beds or be conformable with adjacent inclined strata (Plate 12a). Palaeocurrent directions are generally highly variable. Diamictons of subtype 7a are gradational with subtype 6b (Plate 8a and 8c).

Subtype 7b

In subtype 7b, poorly sorted, gravelly diamictons occur as horizontal beds of uniform thickness interbedded with horizontally stratified and planar and trough cross-stratified sands and gravels (Plates 8b and 12b). Ripple bedding also occurs. In some areas bedding dominantly dips toward the valley side (Plate 12c). The stratified materials are generally well to very well sorted. Clasts are sometimes imbricated and mostly rounded to well rounded in the gravels. The diamictons are usually clast-supported. They

Plate 10a: Variable bed orientations in gravels associated with type 7 (pick at center for scale).

Plate 10b: Lateral variations in grain size distribution and sorting in type 7; note the large boulder bed at the base of the exposure.

Plate 10c: Interbedded, poorly sorted gravels and well sorted sands, associated with diamicton of type 7; note the sudden vertical changes in grain size and sorting.

A

B

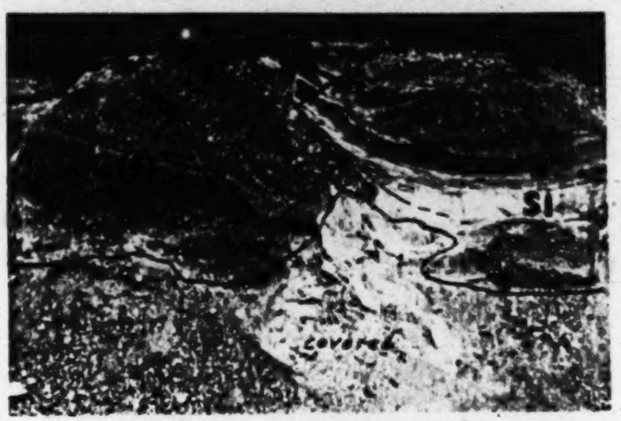
C

Plate 11a: Silts (Si), sands (S) and gravels (G) associated with type 7 diamictons; note faults in gravels and high angle of dip of some beds.

Plate 11b: Angular inclusions of gravel (Gi) in deformed sands (Sd) associated with diamicton of type 7.

Plate 11c: Injection of matrix-supported diamicton (Dm) and sand (Sd) into clast-supported diamicton (Dc) and gravels (G) - type 7.

A



B

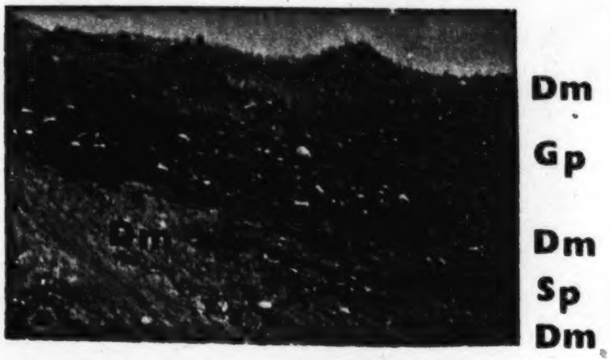
C

Plate 12a: Diamicton (Dm) of subtype 7a (6b?) conformably interbedded with horizontally bedded sands (Sp) and gravels (Gp) in a lens shaped deposit.

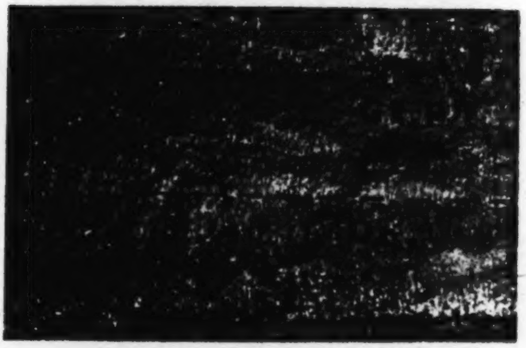
Plate 12b: Gravelly diamicton (Dc) of subtype 7b overlain by trough and planar coss-stratified gravels (Gt,p).

Plate 12c: Clast-supported diamicton (Dc) of subtype 7b interbedded with planar bedded gravels (G) and ripple bedded sands (Sr); note the dip of the beds towards the valley side and weakly developed scour (?) surfaces in the lowest diamicton exposed.

A



B



C

have higher total clast contents and coarser matrix textures than diamictons of subtype 7a (Figures 5 and 6). They may have about a 20% higher local clast content than the associated gravels and generally have more angular clasts. Palaeocurrent directions are usually similar to those in present day streams (i.e. parallel to the valleys) but in some areas sedimentary structures indicate a component of flow towards the valley sides.

Interpretation

Type 7

Diamictons of type 7 are interpreted as debris flows deposited in ice-marginal environments. The interbedding of sorted sediments with the diamictons indicates that individual flow events were isolated by fluvial activity. The abundance of stratified sands and gravels relative to diamicton indicates that fluvial processes dominated the depositional environment. Diamictons of this type are gradational with moderately sorted, stratified, and imbricated gravels interpreted as proximal outwash deposits (Boulton and Eyles, 1979). The gradational nature of these outwash deposits with the diamictons suggests that they originated in the same or adjacent depositional environment. Boulton and Eyles (1979) and Lawson (1979a, 1981a) interpret sediments which are similar in nature to type 7 diamictons and which are often associated with proximal meltwater streams as resedimented tills.

The variability in internal characteristics of diamictons of this type is probably also due to variations in the amount of resedimentation prior to deposition. In most diamicton beds the sandy matrix textures (Figure 5), high clast content (Figure 6), general absence of striations and relatively high degree of sorting and clast roundness all indicate significant reworking of the diamictons by water and gravity prior to final deposition. Resedimentation of deposits, often resulting in the removal of fines and striations, and the concentration and rounding of clasts is very common in the marginal regions of modern glaciers (Boulton and Eyles, 1979, Lawson, 1979a, 1981a). In contrast, some diamictons of this type are unsorted, exhibit striated and angular clasts, are generally matrix-supported with low total clast contents, and show little or no stratification. Such diamictons were likely deposited shortly after being released from their ice source and therefore underwent little or no resedimentation.

Features common to multiple superimposed flows (see discussion of type 6) are generally not present within the diamictons, although local, weakly developed, scour surfaces (Plate 12c), and some stratification within the diamictons suggest that multiple or 'pulsating' events might have occurred. The infrequency of debris flow deposits in this type compared to type 6, is probably due to the relative dominance of fluvial activity.

Deposits of this type are mainly supraglacially derived as indicated by the clast angularity, general lack of striations, enhanced sorting, low density, and dominance of non-local, far-travelled, lithologies characteristic of supraglacial tills (Sharp, 1949; Drake, 1971; Flint, 1971; Boulton, 1976; Boulton and Eyles, 1979). Textural analyses of tills of this type also indicate that they were supraglacially derived. Boulton and Eyles (1979) reported that supraglacial tills have silt and clay contents generally below 15% as is the case for deposits of type 7. The open square on Figure 6 is from Boulton and Eyles (1979, p.14) and represents the modal bulk texture of 28 samples of supraglacially derived debris. They used textural differences as the main distinction between supraglacially derived and subglacially eroded debris. Such a distinction could not be made solely on the basis of texture in areas where the bedrock is largely dominated by fine grained rocks. In addition, significant washing of basally derived debris may produce deposits with coarse textures.

Diamictons of type 7 which are dominated by clasts of local lithology occur in a few areas where the bedrock is soft, poorly indurated shales and siltstones suggesting that this type locally may also be derived from basally transported debris. The basally derived debris flows probably originated in push moraines formed in the soft local bedrock. The angularity of the clasts and lack of striations suggests that it is unlikely that the debris was transported to the ice surface along shear zones before flowing as observed by Boulton (1968) on Vestspitsbergen glaciers. In general, deposits of this variety occur at lower positions in the valley than other deposits of type 7 which have been supraglacially derived.

Some of the deposits of type 7 are believed to have been deposited in lateral rather than frontal ice-marginal positions. This is indicated by the presence of transverse palaeocurrent directions which suggest palaeo-flows toward the valley sides from the valley centers as well as by the common occurrence of this till type in lateral terraces along major valley sides.

Subtype 7a

Diamictons of subtype 7a are interpreted as debris flows onto proximal proglacial outwash deposits. The poor sorting, absence of stratification, low total clast content, and presence of striated and angular clasts in the diamictons suggest that little fluvial reworking occurred after deposition. Mass movements of debris from the ice surface onto adjacent fluvial sediments would result in varying degress of reworking of the deposits. The amount of reworking would be dependent on:

1. stream discharge at the site of deposition, and
2. the rate and volume of sediment input.

Where large quantities of debris are available or discharges are low, streams are often unable to transport the available sediment load and the resultant "outwash" deposits may be very similar to the parent till. During a high flow all available debris may be transported and deposited simultaneously as a planar bed of matrix-supported diamicton (Boulton and Eyles, 1979).

The high variability in sorting and grain size of the sands and gravels of subtype 7a indicates that they were deposited in streams with large fluctuations in sediment input and discharge. Discharges in proximal reaches of outwash streams are subject to large diurnal and annual changes and they are much more variable and flood prone than discharges in downstream, distal locations (Boulton and Eyles, 1979). They noted that the "rapid buildup and decay to and from flood discharges" and the availability of resedimented glacial deposits "has a strong effect on fluvial sediment character" (Boulton and Eyles, 1979, p17).

The presence of deformation, load and fluid injection structures, suggests that the sediments were saturated, as would be expected if deposition was associated with fluvial activity. The presence of diamicton beds that conform to the geometry of adjacent stream channel deposits indicates that some debris flowed into active meltwater stream channels, temporarily or permanently interrupting fluvial sedimentation at the site.

The geomorphic association of this type with the upper portions of terraces located along valley walls, indicates that they may be lateral kame terrace deposits. The proximity of glacial ice during the deposition of this subtype is supported by the presence of folded, faulted and highly dipping beds (suggesting collapse caused by melting of adjacent ice or pushing by active ice) and dropstones in silt beds.

Subtype 7b

Diamictons of subtype 7b are interpreted as resedimented debris flow deposits. The higher clast contents, coarser matrix textures and better sorting suggest a greater degree of reworking than in subtype 7a. Deposits of this subtype are gradational with, and may be indistinguishable from, proximal outwash deposits. In areas where ephemeral streams of high discharge have access to readily eroded sediment, deposits of this nature are an important component of subaerial proximal outwash (Boulton and Eyles, 1979, p19).

Subtype 7b may in some cases represent the deposits of a more distal ice-marginal environment than subtype 7a, as indicated by the higher degree of reworking of the sediments. The better sorting, more regular stratification, and dominance of rounded and well rounded clasts of non-local lithology in gravels of this subtype all indicate that they were subjected to a greater degree of fluvial reworking than subtype 7a and possibly were deposited in more distal environments. This data in conjunction with the observed sedimentary structures and palaeocurrent directions in some areas indicate that the depositional environment was likely a braided outwash stream flowing some distance from a glacier margin. Comparison of this subtype with proglacial deposits at the modern Athabasca Glacier suggest that it may occur as much as 0.5 km from the glacier margin. However, similar deposits occur much closer to the ice margin in areas where fluvial activity is more dominant. Sediments of subtype 7a comprised of beds with consistent dips toward the valley center (Plate 12c) may have been deposited in relatively proximal positions along the lateral margins of valley glaciers.

The significant amount of washing that may have occurred in some diamictons of type 7b indicates that they are not "true tills" as defined in chapter 1. However, they are included in this study because of their gradational nature with more typical resedimented diamictons interpreted as flow tills.

I. Type 8: Massive diamicton interbedded with horizontally laminated silts and clays

Description

Type 8 consists of massive diamicton beds interbedded with horizontally laminated clays and silts (Plate 13a). Silt and clay beds vary in thickness from a few millimeters to tens of centimeters. Diamicton beds are generally several centimeters to several meters thick. Sand and gravel lenses are occasionally associated with deposits of type 8 (Plate 13a). Type 8 is common only in isolated parts of the Snake Indian and Rocky River valleys (Figure 2) and is rare elsewhere. Consequently, detailed descriptions of this type are lacking.

The diamictons are generally clay rich (Figures 5 and 6) and matrix-supported with only 10 to 20% clasts. Most clasts are subangular to rounded and they frequently have striated surfaces. The diamictons exhibit no internal structures except for rare, faint laminations which are usually folded and convoluted. The lower contacts of diamicton beds are irregular and may exhibit load structures. Large clasts within the diamictons may protrude into the underlying sediments and deform bedding. Diamicton beds are usually less than one meter in thickness. They are often lens shaped, pinching out laterally over distances of several meters and often complexly intercalated with silts and clays.

Horizontal laminations within the silts and clays are very common but they are often deformed near the contact with overlying diamicton beds. Scattered clasts occur within the silts and clays.

Where this type is overlain by massive diamictons (type 1), the abundance and size of clasts within the silt and clay beds increases towards the top of the deposit as does the number and thickness of diamicton beds and sand and gravel deposits. This type is usually successively underlain by a thick sequence of lacustrine sediments and fluvial gravels (Plate 13b).

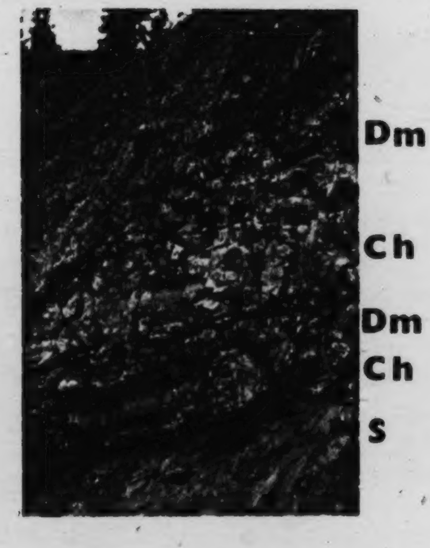
Interpretation

Diamictons of this type are interpreted as glacially derived debris flows which moved along the bottoms of ice-marginal lakes. The associated silts and clays are interpreted as glaciolacustrine sediments deposited between flow events. Their horizontal

Plate 13a: Diamicton (Dm) interbedded with horizontally laminated clays (C) - type 8; note the sand lens (S) at the base of the photo.

Plate 13b: Horizontally stratified silts and clays (Ch) and gravels (Gh) underlying type 8 deposits in the Snake Indian River Valley.

A



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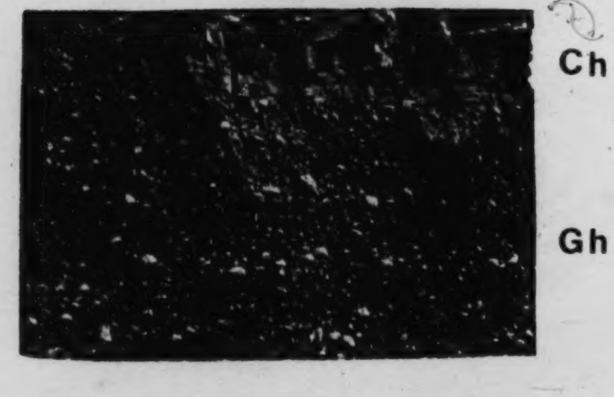


laminae, fine grain size, and excellent sorting indicate deposition in quiet water primarily by settling from suspension. Clasts within the clays are usually striated indicating a glacial origin. They are too large (up to about five centimeters in diameter) in relation to the associated silts and clays to have been transported by traction currents. Consequently they are believed to be dropstones.

An irregular and loaded contact at the base of diamicton beds and deformed bedding immediately underlying the contact, suggest rapid deposition of the diamictons over unconsolidated deposits. Probable flow structures (contorted and folded laminations) within the diamictons support this suggestion. When these characteristics are present in diamictons of this type, they largely preclude an origin by rainout below floating ice as described by Gibbard (1980), Eyles and Eyles (1983) and Miall (1983). The thickness, extent and geometry of the diamicton beds are also consistent with an ice-marginal, subaquatic, debris flow interpretation.

The source of material for the debris flows is believed to be glacial debris derived from the glacier bed as indicated by the fine matrix textures and abundance of striated clasts. The debris may have accumulated either:

1. subaquatically by undermelting of the ice margin (McCabe et. al., 1984; Powell, 1983), or
2. on the ice surface along shear zones where basal debris was exposed, subaerially or subaquatically, by ablation processes (Evenson et. al., 1977; Boulton, 1968, 1971).

Sedimentation in both of these environments would result in a complex of deposits similar to those described above. A recent review of glacial, subaquatic debris flows has been provided by Eyles et.al. (1985).

More study on deposits of this type may allow for the recognition of subtypes and more detailed interpretations on the depositional environments of the deposits. These interpretations would be aided by information on lake parameters such as depth and surface area drawn from palaeogeographic reconstructions of the individual lakes involved.

IV. Glacial deposition in the Portal Creek Area - a case study

A. Introduction

In this chapter the descriptions and interpretations of tills presented in Chapter 3 are used to illustrate the application of the till classification system to glacial stratigraphy in the mountain environment. The Portal Creek area was chosen as the site of this case study for several reasons:

1. Several good exposures of glacial sediments, each containing a number of stratigraphic units, occur in the area.
2. Variations in the bedrock geology of surrounding regions makes till provenance, as determined by pebble lithology, a useful tool in providing some independent stratigraphic control.
3. A wide variety of till types are present in the area.
4. The Portal Creek sections are important to determining the glacial history of the Jasper region as a whole because they occur across the possible terminal region of a distinct glacial event, as indicated by geomorphic evidence, and they represent one of the most complex stratigraphic sequences in the study area.

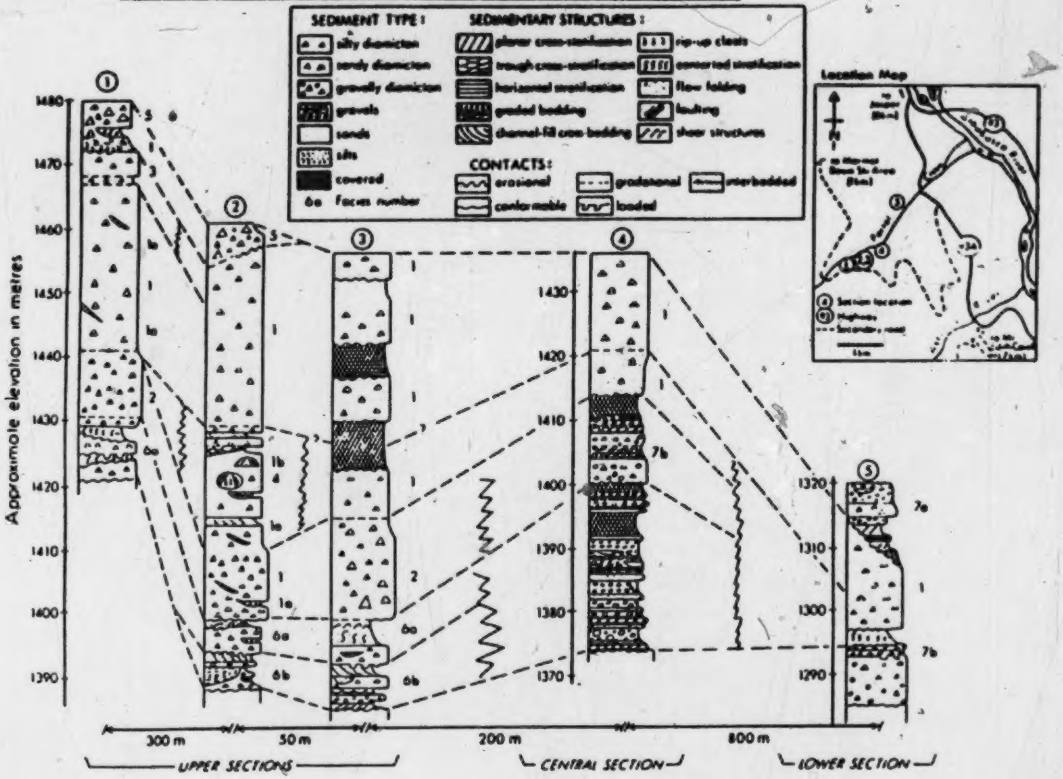
The sequence of deposits in the Portal Creek area are discussed within a stratigraphic context, beginning with the oldest sediments. [illegible] interpretations of the deposits are also presented within this context. The stratigraphic implications of the environmental analysis are then discussed. Finally, the glacial history of the area is presented.

Regional Setting

The Portal Creek sections are located approximately 10 km south of Jasper townsite (Figure 23). The road to Marmot Basin ski area crosses Portal Creek and provides access to the sections.

The exposures occur in the vicinity of the junction of two major valleys which are oriented at near right angles. Portal Creek flows from the southwest (about 250°) into the northwest - southeast (330° to 150°) trending Athabasca River valley. The deposits exposed along Portal Creek, therefore, may have been transported to the area by ice

Figure 23: *Stratigraphic Columns - Portal Creek Area, Alberta.*



moving down the the Athabasca valley and/or the Portal Creek valley.

Bedrock Geology

The local bedrock in the Portal Creek area is largely Miette Group shale, sandstone, and conglomerate with minor siltstone and dolomite (Mountjoy and Price, 1984). Bedrock in the Athabasca valley south of the Portal Creek junction, consists of Miette Group rocks and Gog Group quartzose sandstones, shales and minor dolomite (Campbell, 1971). Middle and Upper Cambrian carbonates are also present in the upper Athabasca and Sunwapta valleys. Quartzose sandstones of the McNaughton Formation (Gog Group) dominate the higher elevations in the Portal Creek watershed. Middle Miette Group grit and sandstone, with some shale and siltstone outcrop in the lower Portal Creek watershed.

The only major source of limestone in the region is the Cambrian formations in the upper Athabasca and Sunwapta river valleys (Campbell, 1971). The limestone Mural Formation of the Gog Group is not known to outcrop in the Portal Creek valley north of 52° 45'. Due to the absence of detailed mapping south of this latitude, it is not known if limestones are present in the southern part of the Portal Creek watershed. However, the limited aerial extent of this possible outcrop area indicates that, if present, limestone outcrops are not large.

Due to these major differences in the bedrock composition between the Athabasca River and Portal Creek valleys, the provenance of the exposed tills can be determined. Deposits originating in the Portal Creek valley should be enriched in coarse clastics and depleted in fine clastics, compared to deposits from the Athabasca Valley. Deposits derived from the Portal Creek watershed should contain little or no limestone since few or no limestone outcrops occur in the Portal Creek watershed.

The bedrock variability also aids in some genetic interpretations of tills in the region. For example, the valley bottoms are dominated by pelitic rocks while higher elevations are dominated by coarse grained clastics (Mountjoy and Price, 1984) thus aiding in the distinction of supraglacially and subglacially derived sediments.

B. Stratigraphy

Introduction

Five exposures of Quaternary sediments along Portal Creek were described in detail in the field. Stratigraphic columns for each of these sections and a location map are provided in Figure 23. The stratigraphy of the Portal Creek region is discussed below by area. The three uppermost (southwestly) sections, which are stratigraphically similar, are discussed together.

Lower Portal Creek Area

The lowest exposed sediments in the lower Portal Creek area are clast-supported diamictons that grade into poorly stratified, coarse gravels interbedded with sands (Column 5, Figure 23). Clasts in the gravels and associated diamictons are weakly imbricated and show no striations. They are mainly sandstone and quartzite (60%), shale (20%) and siltstone (20%). Minor quantities of dolomite and no limestone are present, indicating a Portal Creek provenance. Strata dip gently to the northeast, parallel to the present day stream. The upper portion of these sediments are interbedded with matrix-supported diamictons of type 7. The diamictons occur as beds up to 0.5 m thick which are laterally continuous for 20 m or more and have sharp, planar upper and lower contacts. The latter are sometimes stongly undulating although still very sharp. The associated gravel beds are generally 1-2 m thick and dominate the unit although the diamictons become more abundant towards the northeast.

These sediments are unconformably overlain by moderately well sorted and stratified sands which are deformed, faulted and truncated by a diamicton of type 1 (Column 5, Figure 23). A complex deposit of sand, gravel and diamicton of type 7 unconformably overlies the diamicton and extends to the surface. The diamictons exposed in the upper part of this section all have relatively high limestone contents indicating an Athabasca Valley provenance.

Central Portal Creek Area

The base of the central exposure in the Portal Creek area is dominated by gravels (Column 4, Figure 23). The relatively high limestone content of the gravels (8%) indicate at least some input from the Athabasca valley drainage system. The middle of this section is poorly exposed but gravels appear to be interbedded with gravelly diamicton (type 7) and overlain by massive diamictons of type 1. All of the diamictons at this section appear to be derived from the Athabasca valley as indicated by limestone contents ranging from 16 - 20%.

Upper Portal Creek Area

The lowest exposed sediments in the upper Portal Creek area are intercalated sands, gravels and diamictons (till type 6) overlain by a relatively thick, massive, diamicton of types 1 and 2 (Columns 1-3, Figure 23). The lithology of pebbles from these sediments indicates a Portal Creek provenance (Figures 24 and 25). Clasts are mainly coarse clastics (60 - 66% sandstone, quartzite, and pebbly conglomerate) and fine clastics (29 -39% shale and siltstone). Limestone does not occur in the interbedded sand, gravel and diamicton and the average limestone content of the overlying massive diamictons is 2% (Appendix 4).

A thick sequence of matrix-supported, silty diamicton (till type 1 and subtypes 1a and 1b) of Athabasca valley provenance overlie the above sediments (Columns 1-3, Figure 23). The diamictons are characterized by high total carbonate (18%), limestone (12%) and fine clastic (32%) contents (Figures 24 and 25). The diamictons contain numerous sand lenses (till type 4) in one location (Column 2, Figure 23) and they are locally banded (till type 3) in their upper part (Column 1, Figure 23).

The uppermost sediments at Portal Creek (Column 1 and 2, Figure 23) are diamictons with a high boulder content (Plate 5). Quartzite boulders with diameters up to 5 meters are common. These sediments are readily distinguished from the underlying deposits by differences in color (Plate 5b), texture, and petrology (Figures 24 and 25). The abundance of coarse clastics (70%) and low percentage of limestone (2%) indicate a source area in the Portal Creek watershed rather than the Athabasca valley. These uppermost diamictons thin rapidly and eventually disappear to the northeast (Figure 23).

Figure 24: Lithology of Stratigraphic Units - Portal Creek Area
(Sandstone vs shale/dolomite and limestone)

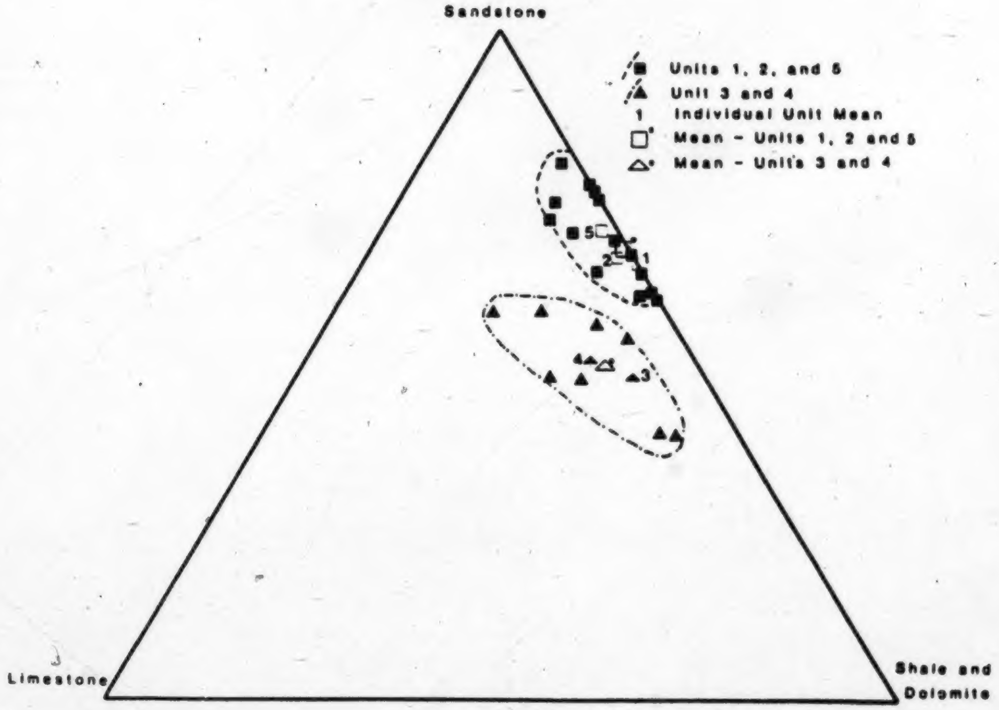
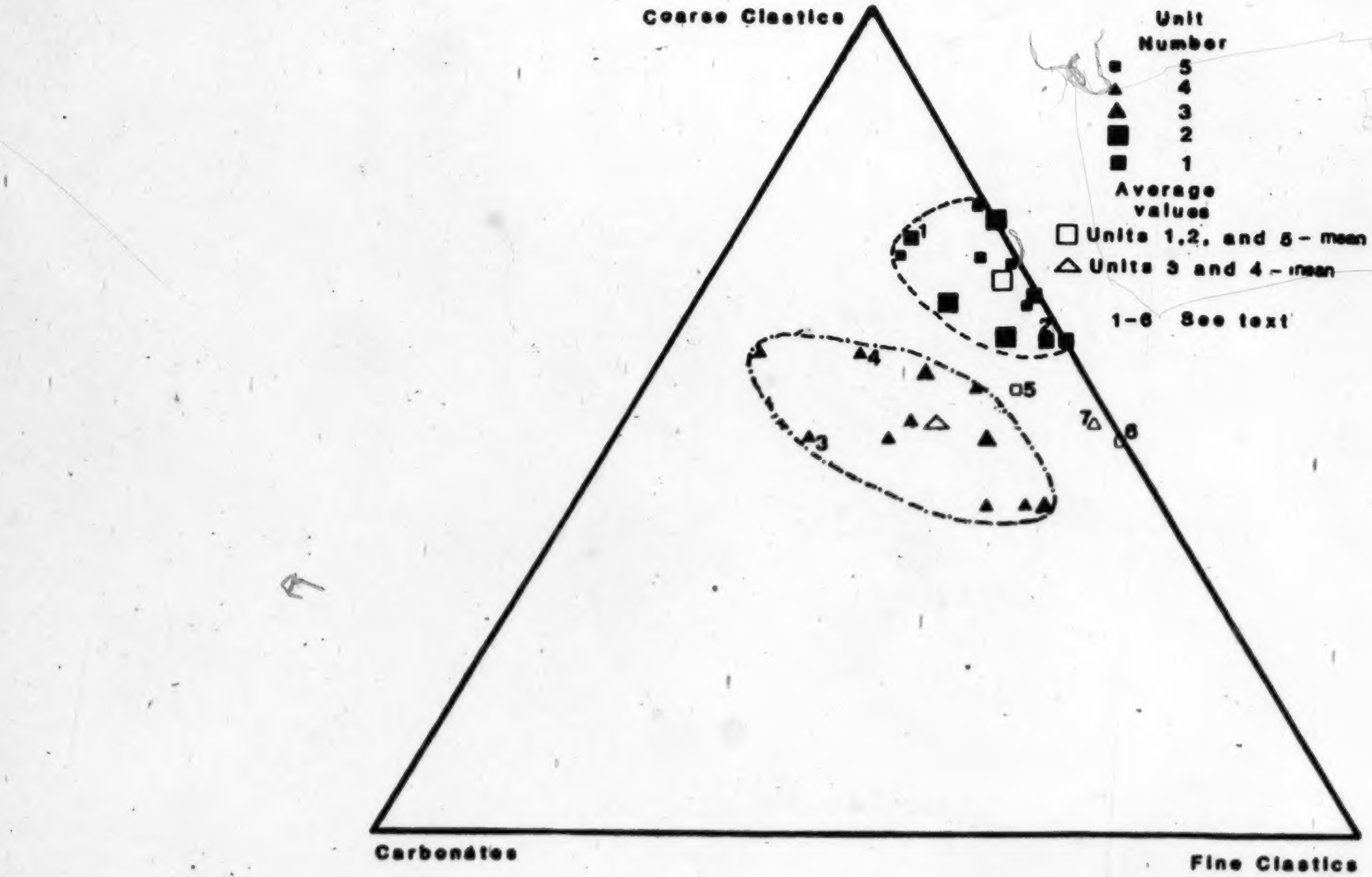


Figure 25: Pebble lithology (clastics vs carbonates) of stratigraphic units in the Portal Creek area



Summary

The lowest exposed sediments in the Portal Creek area are clastsupported diamictons and gravels which extend into the Athabasca valley. They are derived from the Portal Creek valley. Higher up the valley, where Portal Creek first emerges into the Athabasca valley, these sediments have been eroded or are presently covered by younger deposits. In the lower Portal Creek area (columns 4 and 5, Figure 23) these deposits are overlain by sands and gravels derived at least in part from the Athabasca valley. The sands and gravels are in turn overlain by glacial diamictons and associated deposits of Athabasca valley provenance (Columns 4 and 5, Figure 23). In the northeastern most exposure (Column 5, Figure 23), a complex of diamictons and sorted materials overlies a large erosional unconformity.

The complex sequence of deposits in the upper Portal Creek valley can stratigraphically be divided into several units based on lithology, sediment type and provenance. The lowest exposed sediments in this area are glacial diamictons and associated sand and gravel deposits of Portal Creek provenance. These are overlain by a thick sequence of tills derived mainly from the Athabasca valley. The youngest glacial deposits in the area are tills also of Portal Creek provenance.

C. Interpretation of depositional environments

Lower and Central Portal Creek Area

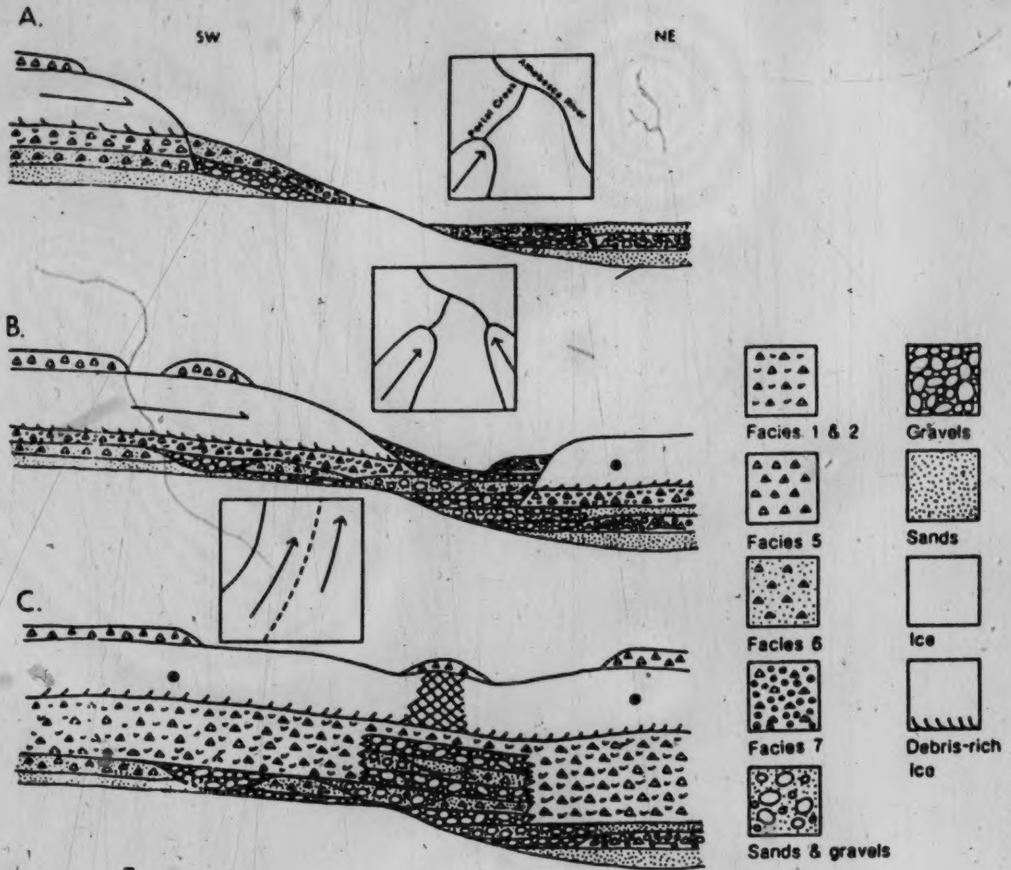
The vertical facies sequence in the lower Portal Creek valley (column 5, Figure 23) follows the expected sequence for a single glacial episode. Non-glacial alluvial fan deposits dominate the lowest part of the sections there. Horizontally stratified, clast-supported, coarse gravels associated with stratified sands and gravelly diamicton have been commonly observed in alluvial fans (Rust, 1979). The predominance of these facies as well as the general dip of strata parallel to the Portal Creek valley, suggest that they are alluvial fan deposits. The absence of limestone erratics and striated clasts and the stratigraphic position of the unit support this interpretation. Lithologic analysis and paleocurrent data suggest a source area to the southwest in the upper Portal Creek basin. In their upper part, these alluvial gravels are interbedded with thin diamictons (type 7) derived from the Athabasca valley. The interbedding of the diamictons with sands and gravels and their small thickness, restricted lateral extent, and coarse textures indicate that they were deposited in this area as intermittent proglacial flows emanating from Athabasca ice up the valley (Figure 26a).

Diamictons of type 1 overlie these deposits (Column 5, Figure 23). The sharp planar contact at the base of these diamictons and compressive deformation (folding and shearing) in the underlying sands suggests that ice overrode the area. The massive, type 1 diamictons in this area are probably basal tills deposited by this ice as indicated by the abundance of striated clasts of local lithology and a strong unimodal pebble fabric. These diamictons are unconformably overlain by glaciofluvial sand and gravel deposits. The unconformity is probably the result of fluvial erosion which occurred in immediate post-glacial times by meltwaters channelled to the valley center. The amount of erosion is not known but ten or more meters of fluvial sediment overlie the till (Column 5, Figure 23). The outwash deposits overlying the unconformity are interbedded with sandy diamicton of type 7, interpreted as proglacial flow tills deposited during retreat of Athabasca ice.

Athabasca valley ice must have initially been restricted to the lower parts of the valley as the thick basal tills in the lower Portal Creek valley (Column 5, Figure 23) grade laterally into outwash sands and gravels in the central Portal Creek valley (column 4, Figure 23). The sands and gravels were likely deposited in a lateral, ice-marginal position (Figure 26b). This interpretation is supported by the presence of diamictons of type 7, interpreted as lateral, ice-marginal debris flow deposits, interbedded with the sands and gravels in their upper portions (Column 4, Figure 23).

All of the glacial deposits in the lower Portal Creek area are of Athabasca provenance. Glacial diamictons of type 6 of Portal Creek provenance increase in abundance upvalley (to the SW) and dominate the lowest exposed sediments in that area (Columns 1-3, Figure 23). Thus, the lateral facies change from Portal Creek till in the SW to sands and gravels and finally to Athabasca till in the NE suggests that the sands and gravels were deposited in an ice free environment between Athabasca and Portal Creek ice. The dominance of type 1 diamicton, interpreted as basal till of Athabasca provenance in the upper parts of the central and lower Portal Creek sections (Columns 4 and 5, Figure 23), suggests that Athabasca ice eventually overrode the entire area (Figure 26c).

Figure 26: Schematic diagram representing early glacial deposition in the Portal Creek area: a) deposition of proglacial flow tills in front of the advancing Portal Creek and Athabasca valley glaciers; b) deposition of glaciofluvial gravels and lateral till flows between the two glaciers; c) deposition of basal tills throughout the area.


A.
SW
NE
B.
C.
Facies 1 & 2
Facies 5
Facies 6
Facies 7
Sands & gravels
Gravels
Sands
Ice
Debris-rich
Ice

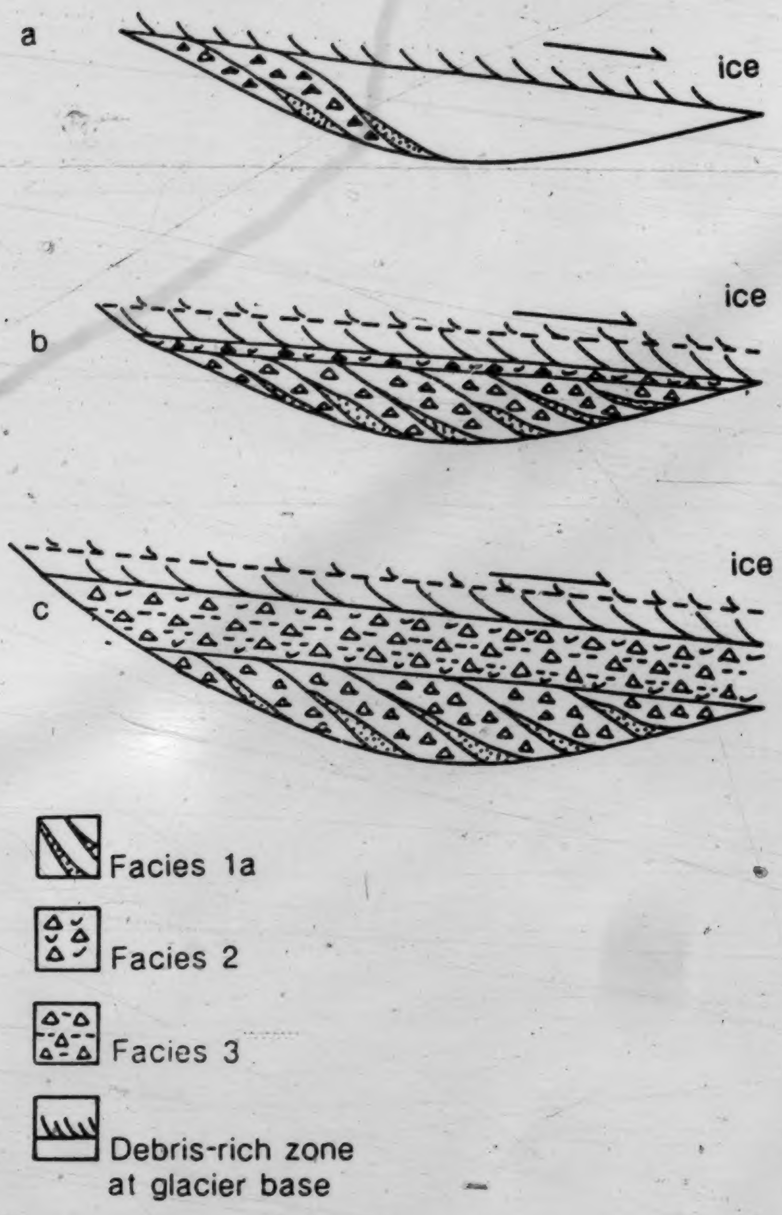
Upper Portal Creek Area

In the northeastern part of the Portal Creek area diamictons of type 6, interpreted as the deposits of debris flows from a glacier terminus, dominate the lower part of the sections (Columns 1-3, Figure 23). Till type 6b grades vertically upwards into type 6a at several localities. A similar facies change occurs laterally from the northeast to the southwest at the same stratigraphic level with type 6b dominating in the southwest (Columns 1-3, Figure 23). This vertically upwards and laterally southwestwards transition from till type 6b to type 6a (interpreted, respectively, as distal and proximal proglacial till flows) suggests the movement of ice into the area from the southwest (Figure 26a) This interpretation is supported by the increase in sand and gravel deposits of fluvial origin towards more distal locations to the northeast as well as by till provenance studies. In addition, the proximal deposits of till type 6a are everywhere overlain by massive diamictons of types 1 and 2, interpreted as basal tills deposited by the advancing Portal Creek glacier.

The diamictons of type 2, interpreted as lodgement tills, grade vertically upwards and laterally into those of type 1 which dominates most of the upper Portal Creek sections (Columns 1-3, Figure 23). The intimate association of these different till types is believed to be the result of similarities in genetic origin. Type 1 is broadly interpreted as a basal till and thus may be genetically related to any of the other more narrowly interpreted till types of basal origin. Where a massive till of type 1 is intimately associated with some other basally derived till, for example type 2, it is likely that both originated in the same way (i.e. by lodgement in this example). Thus, the association of types 1 and 2 in the lower part of the Portal Creek sections (Columns 1-3, Figure 23) suggests that the sediments there were largely deposited by lodgement at the base of Portal Creek ice (Figure 26).

Lithological and pebble fabric analysis indicate that most of the diamicton in the central part of the upper Portal Creek sections is largely of Athabasca valley provenance and was probably deposited by ice that flowed transversely across the Portal Creek valley (Figure 26c). The movement of Athabasca ice, transverse to the valley created by Portal Creek would have resulted in eventual infilling of the latter by glacial debris (Figure 27). Till deposited in analogous environments has been termed 'lee-side till' by Haldorsen (1982).

Figure 27: Schematic diagram representing the deposition of lee-side till during full glacial times: a) deposition of flow tills and small sand and gravel deposits in subglacial cavities; b) complete infilling of subglacial cavities and deposition of lodgement till; incipient development of a shear zone within the glacier; c) formation of meltout till from layers of debris-rich ice stranded beneath active ice; deposition of lodgement till at the base of active ice; development of new shear zones at progressively higher positions within the glacier.


a
ice
b
ice
c
ice
Facies 1a
Facies 2
Facies 3
Debris-rich zone at glacier base

An analysis of the vertical facies sequence within the central portions of the sections shows that type 1 is complexly associated with subtype 1a. Sand lenses and elongated pebbles within subtype 1a show a preferred downvalley plunge parallel to the Athabasca valley. Till type 1a is interpreted as a lee-side till. Its common occurrence and association with till type 1 suggests that most of the diamicton in the central part of the upper Portal Creek sections accumulated at the base of the Athabasca valley glacier in a lee-side locality (i.e. in the bedrock depression created by Portal Creek) (Figure 27). The preferred plunge is a result of the deposition of material along the slopes of the preexisting Portal Creek valley by overriding Athabasca ice. A decrease in the magnitude of the preferred plunge upsection, supports this interpretation since the slope of the valley walls would decrease as the valley was infilled (Figure 27).

The actual mechanism of deposition of subtype 1a and the associated diamictons in this area may have been by lodgement, meltout, or flow into basal cavities. If a subglacial cavity formed under this glacier in the bedrock depression created by the Portal Creek valley, it probably developed at an early stage when infilling of the latter was at a minimum and the valley slope was relatively steep (Figure 27a). Thus, the depositional mechanism may initially have been the flowage of debris into subglacial cavities in a manner similar to that observed by Boulton (1970, 1971) at the base of modern Spitsbergen glaciers. The abundance of sand lenses in the lower part of these diamictons (central part of column 2, Figure 23) and their absence in stratigraphically higher deposits (Columns 1 and 2, Figure 23) supports this interpretation, as subglacial stream channels would be expected in an open cavity system. Continued infilling of the cavity with subglacial debris would eventually have allowed for the overriding glacier to come into contact with, and conform to, the subglacial topography (Figure 27b).

A meltout origin for much of the diamicton in the upper Portal Creek sections is suggested by the presence of till types 1b and 3, interpreted as basal meltout tills, and type 4, interpreted as englacial meltout till (Columns 1 and 2, Figure 23). In addition, massive till of type 1 is complexly associated with types 1b, 3 and 4 (Columns 1 and 2, Figure 23) and may also have been deposited by meltout. This would require that a sufficient thickness or concentration of debris-rich ice was present to account for the large cumulative thickness of these diamictons. Debris concentrations up to 80% have been reported for some modern temperate glaciers (Boulton, 1968, 1975; Lawson, 1979a) but generally such debris rich bands are in the order of centimeters or meters in thickness and not tens of meters. However, accumulations of meltout till of greater thicknesses would be possible if the basal shear zone in a glacier overriding an area of relatively depressed topography, gradually moved up into the ice thereby stranding a succesive series of debris rich blocks in the subglacial depression (Figure 27). Thus, the thickness of the accumulating meltout till would be limited only by the depth of the depression.

In this model, debris deposited along the active shear zone (lodgement till) would be intimately associated with till melting out from underlying debris rich layers. In addition, shear zones may have become reactivated after some meltout had already occurred, or new shear zones may have developed in subglacial debris previously deposited by meltout mechanisms. Consequently, a gradation between lodgement and meltout till would be expected. The diamictons in the central part of the upper Portal Creek sections exhibit characteristics that, depending on the area, are typical of either lodgement till, meltout till (either basal or englacial), or some intermediate variety of the two types. A similar gradation between genetic varieties of till was observed in lee-side localities by Haldorsen (1982).

Thus, since a subglacial cavity probably existed, at least initially, in the area, thereby allowing for subglacial flows, and since the above interpretaton of depositional environment and observed properties of the deposits indicate that both meltout and lodgement tills are present, it seems likely that all these processes played a role in the deposition of the lee-side tills. In the absence of sedimentary structures (ie. where only facies 1 can be recognized), a detailed comparison of such factors as number of striations, clast shape, compaction and texture may identify one of the above three processes as a more likely depositional mechanism than the others for any one locality. However, since the till in all three cases would have been eroded from upvalley, carried for a short distance in the basal zone and deposited in a restricted area, it is unlikely that any of these characteristics will be diagnostic. More detailed sedimentologic studies will be required to determine the exact process responsible for the deposition of lee-side tills at specific localities.

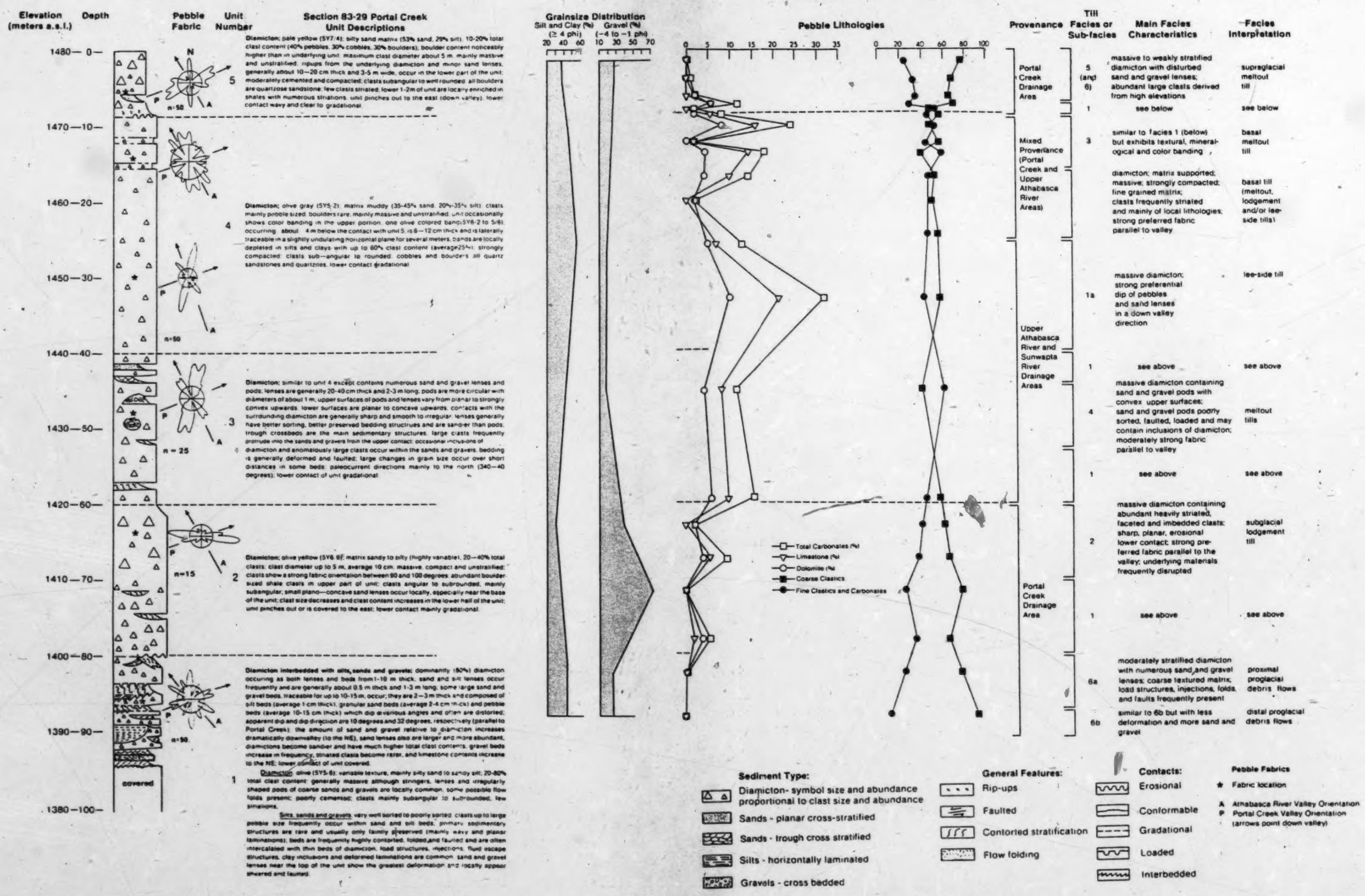
The lower contact of the surface unit in the upper Portal Creek area varies from gradational to clear and wavy (Columns 1 and 2, Figure 23). The nature of this contact, together with the increase in fine clastic content and the presence of rip-up clasts in the lower portion of the surface unit, indicates that the contact is an erosional unconformity. The upper part of the sequence of deposits formed by Athabasca valley ice thus appears to have been partially eroded and the stratigraphic sequence is therefore not complete.

Three diamicton types can be recognized in the surface unit in the upper Portal Creek area (Columns 1 and 2, Figure 23). A massive diamicton (type 1) occurs locally in the lower part of the unit. The abundance of striated clasts indicates a basal origin but the dominance of shale may in part be the result of incorporation of sediment from the underlying shale-rich unit deposits. The low limestone content at the base of the surface unit, however, indicates that these basally derived sediments originated in the Portal Creek valley and not in the Athabasca valley as is the case for most of the underlying sediments. The upper portion of the surface unit is largely composed of diamictons of type 5, interpreted as supraglacial flow tills, which grade laterally and vertically into type 6, interpreted as proglacial till flows. In this area the proglacial flows are supraglacially derived and, therefore, difficult to distinguish from till type 5. The scarcity of sand lenses in this area makes the distinction between deposits of supraglacial and proglacial origins difficult.

D. Stratigraphic Implications

The environmental analysis of the facies present in the Portal Creek area has several stratigraphic implications. Lithologic studies of clasts in tills suggest that the area was influenced at different times by ice originating in separate valleys. The lithologic variations are most complex in the upper Portal Creek area. A composite stratigraphic column of the upper Portal Creek area is provided in Figure 28. A traditional stratigraphic grouping of the deposits, based on textural and lithologic analysis of the tills, is provided on the left-hand side of Figure 28. Five stratigraphic units can be recognized. These in turn can be grouped into three sedimentary packages of distinct provenance (Figure 28, center). The lowest exposed sediments in this area (Units 1 and 2, Figure 28) are glacial diamictons and associated sand and gravel deposits of Portal Creek provenance. These are

Figure 28: Composite stratigraphic column of the upper Portal Creek area; lithostratigraphic units are shown on the left; textural and lithologic data are given in the center columns; the facies sequence present and environmental interpretations are shown on the right side.



Section 83-29 Portal Creek Unit Descriptions

5 **Diamicton;** pale yellow (5Y7/4); silty sand matrix (53% sand, 29% silt), 10-20% total clast content (40% pebbles, 30% cobbles, 30% boulders); boulder content noticeably higher than in underlying unit; maximum clast diameter about 5 m; mainly massive and unstratified; ripups from the underlying diamicton and minor sand lenses, generally about 10—20 cm thick and 3-5 m wide, occur in the lower part of the unit; moderately cemented and compacted; clasts subangular to well rounded; all boulders are quartzose sandstone; few clasts striated; lower 1-2m of unit are locally enriched in shales with numerous striations; unit pinches out to the east (down valley); lower contact wavy and clear to gradational.

4 **Diamicton;** olive gray (5Y5/2); matrix muddy (35-45% sand, 20%-35% silt); clasts mainly pebble sized; boulders rare; mainly massive and unstratified; unit occasionally shows color banding in the upper portion; one olive colored band (5Y6/2 to 5/6), occurring about 4 m below the contact with unit 5, is 6—12 cm thick and is laterally traceable in a slightly undulating horizontal plane for several meters; bands are locally depleted in silts and clays with up to 60% clast content (average 25%); strongly compacted; clasts sub—angular to rounded; cobbles and boulders all quartz sandstones and quartzites; lower contact gradational.

3 **Diamicton;** similar to unit 4 except contains numerous sand and gravel lenses and pods; lenses are generally 20-40 cm thick and 2-3 m long; pods are more circular with diameters of about 1 m; upper surfaces of pods and lenses vary from planar to strongly convex upwards; lower surfaces are planar to concave upwards; contacts with the surrounding diamicton are generally sharp and smooth to irregular; lenses generally have better sorting, better preserved bedding structrures and are sandier than pods; trough crossbeds are the main sedimentary structures; large clasts frequently protrude into the sands and gravels from the upper contact; occasional inclusions of diamicton and anomalously large clasts occur within the sands and gravels; bedding is generally deformed and faulted; large changes in grain size occur over short distances in some beds; paleocurrent directions mainly to the north (340—40 degrees); lower contact of unit gradational.

2 **Diamicton;** olive yellow (5Y6/6); matrix sandy to silty (highly variable), 20—40% total clasts; clast diameter up to 5 m, average 10 cm; massive, compact and unstratified; clasts show a strong fabric orientation between 90 and 100 degrees; abundant boulder-sized shale clasts in upper part of unit; clasts angular to subrounded, mainly subangular; small plano—concave sand lenses occur locally, especially near the base of the unit; clast size decreases and clast content increases in the lower half of the unit; unit pinches out or is covered to the east; lower contact mainly gradational.

1 **Diamicton interbedded with silts, sands and gravels;** dominantly (60%) diamicton occuring as both lenses and beds from 1-10 m thick; sand and silt lenses occur frequently and are generally about 0.5 m thick and 1-3 m long; some large sand and gravel beds, traceable for up to 10-15 m, occur; they are 2—3 m thick and composed of silt beds (average 1 cm thick), granular sand beds (average 2-4 cm thick) and pebble beds (average 10-15 cm thick) which dip at various angles and often are distorted; apparent dip and dip direction are 10 degrees and 32 degrees, respectively (parallel to Portal Creek); the amount of sand and gravel relative to diamicton increases dramatically downvalley (to the NE); sand lenses also are larger and more abundant, diamictons become sandier and have much higher total clast contents, gravel beds increase in frequency, striated clasts become rarer, and limestone contents increase to the NE; lower contact of unit covered.

Diamicton: olive (5Y5/6); variable texture, mainly silty sand to sandy silt; 20-60% total clast content; generally massive although stringers, lenses and irregularly shaped pods of coarse sands and gravels are locally common; some possible flow folds present; poorly cemented; clasts mainly subangular to subrounded; few striations.

Silts, sands and gravels; very well sorted to poorly sorted; clasts up to large pebble size frequently occur within sand and silt beds; primary sedimentary structures are rare and usually only faintly preserved (mainly wavy and planar laminations); beds are frequently highly contorted, folded and faulted and are often intercalated with thin beds of diamicton; load structures, injections, fluid escape structures, clay inclusions and deformed laminations are common; sand and gravel lenses near the top of the unit show the greatest deformation and locally appear sheared and faulted.

Provenance	Till Facies or Sub-facies	Main Facies Characteristics	Facies Interpretation
Portal Creek Drainage Area	5 (and 6)	massive to weakly stratified diamicton with disturbed sand and gravel lenses; abundant large clasts derived from high elevations	supraglacial meltout till
	1	see below	see below
Mixed Provenance (Portal Creek and Upper Athabasca River Areas)	3	similar to facies 1 (below) but exhibits textural, mineralogical and color banding	basal meltout till
		diamicton; matrix supported; massive; strongly compacted; fine grained matrix; clasts frequently striated and mainly of local lithologies; strong preferred fabric parallel to valley	basal till (meltout, lodgement and/or lee-side tills)
Upper Athabasca River and Sunwapta River Drainage Areas	1a	massive diamicton; strong preferential dip of pebbles and sand lenses in a down valley direction	lee-side till
	1	see above	see above
	4	massive diamicton containing sand and gravel pods with convex upper surfaces; sand and gravel pods poorly sorted, faulted, loaded and may contain inclusions of diamicton; moderately strong fabric parallel to valley	meltout tills
	1	see above	see above
Portal Creek Drainage Area	2	massive diamicton containing abundant heavily striated, faceted and imbedded clasts; sharp, planer, erosional lower contact; strong preferred fabric parallel to the valley; underlying materials frequently disrupted	subglacial lodgement till
	1	see above	see above
	6a	moderately stratified diamicton with numerous sand and gravel lenses; coarse textured matrix; load structures, injections, folds, and faults frequently present	proximal proglacial debris flows
	6b	similar to 6b but with less deformation and more sand and gravel	distal proglacial debris flows

overlain by a thick sequence of tills derived mainly from the Athabasca valley (Units 3 and 4, Figure 28). The youngest glacial deposits in the area are tills also of Portal Creek provenance (Unit 5, Figure 28). A more detailed breakdown of the deposits, according to diamicton types as defined in chapter 3 of this thesis, is given on the right-hand side of Figure 28. Environmental interpretations of the till types are given in the last column of Figure 28.

The following discussion evaluates the time-stratigraphic significance of the three main sedimentary packages in the Portal Creek area, by applying the information presented in the above environmental analysis of till types. Specifically, the change from deposits of Portal Creek provenance to those of Athabasca valley provenance at the unit 2 / 3 contact and the reverse transition at the unit 4 / 5 contact (Figure 28), are evaluated in the light of genetic interpretations placed on the associated tills to determine whether or not they represent significant time-hiatuses between separate glacial events.

An overall analysis of the interpretation of the vertical distribution of till types shown in Figure 28 reveals that proglacial deposits are overlain by a thick basal till sequence which is in turn overlain by a relatively thin supraglacial till. The natural progression from proglacial to basal to supraglacial deposits at first suggests that the entire sequence was deposited during one glacial event. However, a more detailed analysis indicates that this is probably not the case.

The lowest exposed set of glacial deposits (units 1 and 2, Figure 28) are of Portal Creek provenance and their presence indicates the movement of Portal Creek ice into the area. They are overlain by till (unit 3, Figure 28), largely of Athabasca valley provenance indicating the subsequent movement of Athabasca ice into the area. A transition zone between units 2 and 3 is shown by a gradual upward increase in the limestone and total carbonate content and by a decrease in the coarse to fine clastic ratio. From stratigraphic evidence alone it cannot be determined if this transition from till of Portal Creek provenance to till of Athabasca valley provenance is a result of two separate glacial episodes or merely a result of the expansion of advancing Athabasca ice up the valley sides resulting in a lateral confinement of Portal Creek ice to the southwestern side of the valley. Tills in the transition zone are primarily interpreted as basal tills (types 1 and 2). The absence of any facies containing sorted materials indicative of ice-marginal deposits suggests that ice did not retreat from the area during the period of deposition of units 2 and 3. Consequently, the gradual increase in the limestone content of tills in units 2 and 3 is probably the result of the gradual lateral expansion of the Athabasca valley glacier. This is supported by the presence of type 1 diamictons, interpreted as basal Athabasca valley tills, at much lower stratigraphic levels in the valley center than farther to the southwest (Columns 4 and 5, Figure 23).

In addition, diamictons of type 7, interpreted as lateral ice-marginal debris flows, grade vertically upwards and laterally northeastwards into basal tills (type 1) of Athabasca valley origin (Columns 4 and 5, Figure 28). This suggests that there was active ice depositing basal tills in the valley center while debris was flowing off the SW margin of the ice. Later expansion of the active ice resulted in the deposition of basal tills throughout the area. The vertical sequence from fluvial gravels to gravels interbedded with diamicton of type 7 to glacial diamicton of type 1 is also consistent with the above interpretation.

Fluctuations in the carbonate content of tills in the upper Portal Creek area (units 3 and 4, Figure 28) suggest a mixed Portal Creek and Athabasca provenance. This 'mixing' may have been the result of changes in the relative lateral confinement and expansion of the two glaciers. This interpretation is supported by pebble fabric diagrams for units 3 and 4 (Figure 28) which exhibit principal orientations intermediate between the orientations of the Athabasca and Portal Creek valleys. This suggests the influence of ice from both sources. A similar situation involving two confluent glaciers in the Rocky Mountain Trench has been described by Broster and Dreimanis (1981).

The uppermost unit at Portal Creek (unit 5, Figure 28) is of Portal Creek provenance as indicated by the low limestone content and relatively high proportion of coarse clastics, particularily quartzose sandstones. The difference in provenance between unit 5 and underlying units again suggests that a separate glacial event (a readvance or significant stillstand) may be represented. The following lines of evidence all suggest that this was the case, although none of the arguments presented are conclusive in themselves:

1. The presence of deposits interpreted as both basal and supraglacial tills in unit 5 provides some of the strongest evidence that it was deposited during a different event than the underlying units. However, supraglacial tills are dominant and basal tills are only locally present and difficult to observe in section. The abundance of

fabric diagrams for the two units suggest different ice sources.

5. In the Astoria River valley, just south of the Portal Creek valley, the presence of stratified materials between two major tills similar in nature and stratigraphic position to the upper two till units at Portal Creek also indicates that a separate glacial event did occur in the area.
6. The presence of relatively well developed lateral moraines in the Portal and Astoria river valleys, suggests that a glacial advance of significantly younger age than that represented by most of the deposits at Portal Creek, may have occurred. Extrapolation of these moraines indicates that the southwestern-most Portal Creek sections (Columns 1 and 2, Figure 23) lie near the termination of this event. Unit 5 (Figure 28) may therefore represent the deposits of a terminal moraine. Such moraines, formed by valley glaciers and derived largely from supraglacial debris, have been termed 'lateral-frontal dump moraines' (Boulton and Eyles, 1979). In such a morainal environment, proglacial till flows on and near the snout of the glacier would be expected and deposits similar to till types 5 and 6 would be common.

The regional surface morphology in the Portal Creek area is dominated by gentle flutings which enhance the linear topography produced by the strike of bedrock ridges. The thin supraglacial till cover has little or no surface expression. No well developed terminal moraine is apparent although a low, broad ridge lies across the mouth of the Portal Creek valley. The ridge may represent the terminus of the advance discussed above or it may have formed by colluvial processes which tend to obscure most glacial features in the region. The upper few meters of the Portal Creek sections have experienced some gravity movements, but the amount of disruption must have been minor as indicated by the presence of undisturbed sand lenses.

E. Glacial History of Portal Creek Area

From the stratigraphic and geomorphic evidence given in this chapter and from the above facies analysis, the glacial history of the Portal Creek area can be summarized as follows.

supraglacial till compared to deposits in the Athabasca valley, can be explained by differences in source valley geometry. The narrow steep walls of the Portal Creek valley are much more conducive to rock falls and slides than the broad, gentle sided, Athabasca valley. The local occurrence of the basal deposits can be accounted for by a variety of mechanisms. For example, advancing glaciers do not always deposit a continuous sheet of till at their bases, or, if they do, erosion by subglacial streams may result in local removal of basal sediment.

2. The lithologic change between units 4 and 5 indicates a different provenance for the two units. Lithologic differences, however, may be explained by differences in the genesis of the deposits dominating each of the two units. During the formation of supraglacial deposits, for example, extensive reworking of the sediment during transport and deposition may result in the breakdown of clasts of soft lithology and thus create lithologic differences from other types of till (such as basal tills) with different genetic history but similar parent materials. Still, lithologies are generally consistent even across facies boundaries within units 4 and 5 (Figure 28) suggesting that the lithologic differences between the units are the result of different provenances and not facies changes. Unfortunately, unit 5 is dominated by one main sediment association (till types 5 and 6), and the restricted occurrence of type 1 prohibited detailed lithologic comparisons with types 5 and 6. When till type 1 was observed in contact with types 5 and 6, lithologic analysis indicated a different provenance than the underlying deposits.
3. The erosional unconformity and the presence of a basal till at the base of unit 5, albeit poorly represented, suggests that erosion along the contact was carried out by active ice. The absence of a gravel lag overlying the contact indicates that erosion by meltwater from the potentially large volume of ice between supraglacial sediments and subglacial or basal sediments did not create the unconformity.
4. An analysis of pebble fabric diagrams for units 4 and 5 lends support to the 'two event' theory. The preferred orientation of pebbles in unit 5 is clearly parallel to the orientation of the Portal Creek valley (Figure 28). Unit 4 pebble fabrics more nearly approximate the orientation of the Athabasca River valley (Figure 28). Although the strength of the preferred orientations are not high, the differences between the

Glacial ice moving down the Athabasca valley was initially confined to the valley center (Figure 26) Proglacial flow tills were deposited over pre-existing alluvial sediments originating from the tributary Portal Creek valley. Portal Creek ice spilled out into the Athabasca valley before the latter was fully occupied by Athabasca ice (Figure 26a). Outwash gravels were deposited in a kame-like feature in the intervening area between the two glaciers by meltwater streams emanating from both ice sheets (Figure 26b). Distal debris flows were deposited with the outwash sediments in front of the advancing Portal Creek glacier. These were successively overlain by more proximal proglacial deposits and eventually by lodgement tills deposited by overriding Portal Creek ice. Farther to the northeast, the glaciofluvial sands and gravels deposited along the margins of the Athabasca ice were gradually succeeded by lateral ice-marginal flow tills. Further expansion of Athabasca ice resulted in coalescence with Portal Creek ice and the deposition of basal tills throughout the region (Figure 26c). The overriding ice deformed and sheared the underlying deposits and created a sharp, erosional unconformity in most areas.

Eventually, the much larger accumulation area of the Athabasca valley ice resulted in confinement of Portal Creek ice to the southwestern side of the valley. The northwest-southeast trending margin between these two glaciers appears to have fluctuated, probably as a result of variations in the rate and volume of ice flow down each valley. A thick sequence of lee-side till accumulated in the bedrock depression created by the Portal Creek valley as a result of deposition at the base of these confluent glaciers as they moved transversely across the depression (Figure 27). Subglacial flow, lodgement, and meltout tills were the main types of till deposited. The Athabasca valley glacier dominated for most of the depositional period but till of mixed Portal Creek and Athabasca valley provenance also was deposited, especially in the later stages of glaciation.

The thick sequence of tills deposited in the lower Portal Creek valley were partially eroded following deglaciation. Erosion was concentrated in the valley center where meltwaters were channelled. Proglacial debris flows were locally deposited with outwash deposits during ice retreat.

In the upper Portal Creek valley, erosion of the underlying tills appears to have taken place by ice moving out of Portal Creek. It is not known if Portal Creek ice merely continued to flow after the Athabasca valley glacier had retreated from the area, or if the

Portal Creek glacier readvanced at some later time. Based on sedimentologic data, facies associations, geomorphic evidence from lateral moraines in the region and on preliminary stratigraphic information from the Astoria River valley, it appears that a readvance or major late-glacial stillstand occurred. Glacial ice during this event appears to have flowed down the Portal Creek valley and terminated near its junction with the Athabasca valley. The uppermost unit exposed in the Portal Creek area may represent a thin basal till and a relatively thick supraglacial proglacial till sequence deposited at the terminus of this glacier. The Portal Creek glacier had a more extensive supraglacial cover than Athabasca ice and, consequently, the deposits left during this late stage event were mainly supraglacially derived. A small terminal dump moraine may have developed at the margin of the Portal Creek glacier during this final event.

F. Glacial Chronology

The bulk of the glacial deposits studied in this thesis are believed to be Late Wisconsinan in age. This assumption is based on two radiocarbon dates from materials collected during the course of this study. A finite date of 29,100 ± 560 ^{14}C years B.P. (GSC-3792) was obtained on wood found in outwash sediments underlying a surface till, in the Jasper townsite area (Figure 2). The wood pieces were angular and fragile suggesting that they had not been reworked, from older deposits and that the overlying till is Late Wisconsinan in age. In the Pocahontas area (Figure 2), gastropods were collected from a surface unit of glaciolacustrine silts and clays presumably deposited at the margins of a retreating glacier. They were dated at 11,900 ± 120 ^{14}C years B.P.(GSC-3885) thus providing a minimum date for deglaciation of that area. No prominent geomorphic breaks occur between Pocahontas, Jasper townsite and Portal Creek suggesting that all the surficial glacial deposits in the major valleys in the Jasper region north of the Portal Creek area were deposited in the period effectively bracketed by the above two dates.

Due to the presence of a moraine system which probably terminates in the vicinity of the Portal Creek sections, and for other reasons outlined in the previous section, it is believed that the surface unit at Portal Creek (unit 5) was deposited in a separate glacial event of relatively limited extent. Since no advance of this magnitude has occurred in the last 10,000 years (Luckman and Osborn, 1979; Kearney and Luckman, 1981) this event must also be Late-Wisconsinan in age.

In summary, the Portal Creek stratigraphic record represents two Late-Wisconsinan advances. The earlier advance (represented by units 1-4 at Portal Creek and by surface tills farther north) extended beyond the study area. The later advance was restricted to high tributary valleys such as the Portal Creek valley. Ice moving down the Portal Creek valley probably terminated in the vicinity of the upper Portal Creek sections (Figure 28) where it deposited unit 5. The extent of this later advance in other valleys is presently under investigation.

V. Conclusions

Glacial diamictons described and sampled during regional stratigraphic studies in the Jasper region are categorized into eight types and six subtypes. The classification scheme is based on readily observable field criteria and is therefore useful for regional stratigraphic studies where large numbers of outcrops must be studied in limited time periods. Although only objective criteria are used, the classification was designed to ultimately aid in genetic interpretations of the described deposits which are required for meaningful stratigraphic correlations of glacial sediments. Although the generalized level of the classification makes detailed genetic interpretations impossible in some cases, it is of sufficient detail for most stratigraphic purposes. Detailed study of certain deposits may allow for more specific interpretations. All interpretations are subject to revision and the classification scheme itself will require farther refinement as new types of glacial deposits are encountered in other mountain environments. However, reinterpretations of classified deposits should not require changes to the scheme as the categories themselves are objective.

The till classification developed here is summarized in Table 1. Classification and genetic interpretation are based mainly on:

1. internal characteristics such as lithology and sedimentary structures,
2. vertical and lateral variations within units,
3. the nature of underlying and overlying contacts, and
4. the types of associated deposits.

The eight till types summarized in Table 1 can be grouped into four major categories based on interpretations on the position of formation of the till:

1. basal tills (types 1 to 3)
2. englacial tills (type 4)
3. supraglacial tills (type 5), and
4. ice-marginal deposits (types 6 to 8).

Till types of the first two genetic categories commonly are vertically and laterally gradational with one another. This basal / englacial sediment association occurs, as most type 4 tills apparently formed in the basal debris rich zone (but were still entirely encased within ice at the time of formation). Contacts between till types 1 to 4 usually are conformable farther suggesting a genetic relationship. Similarily, till types of the supraglacial / ice-marginal sediment association usually occur together and grade laterally into one another. Contacts separating till types of the basal / englacial sediment association (types 1 to 4) from those of the supraglacial / ice-marginal sediment association (types 5 to 8) commonly are erosional.

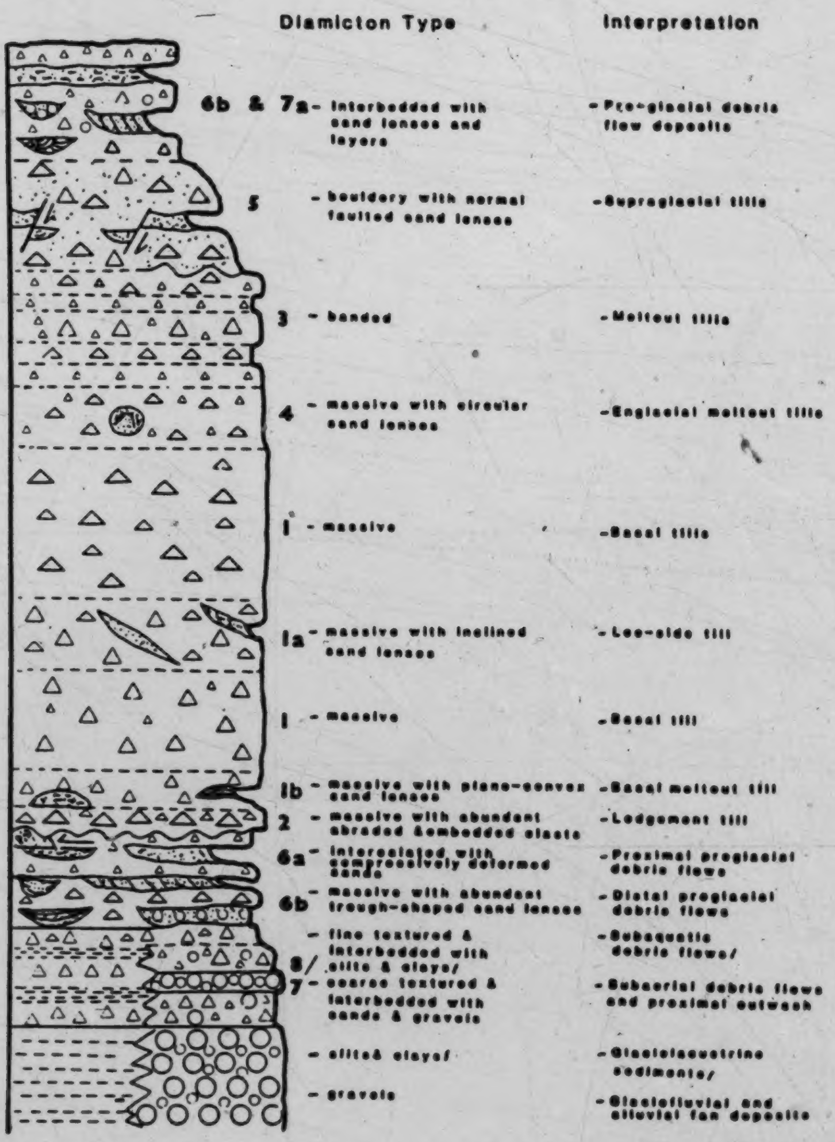
The hypothetical facies sequence given in Figure 29 is based on actual observations on the freqency, thickness and stratigraphic occurrence of each of the till types represented.

The utility of the till classification system presented in this thesis was tested by the analysis of a complex sequence of glacial diamictons in the Portal Creek area. The genetic interpretations placed on the till types were validated by a general agreement between the expected and observed facies sequences, and also proved useful in solving stratigraphic problems in the area as summarized below.

Stratigraphically complex sequences of glacial deposits in the Jasper region, occur mainly in areas where surficial sediments are relatively thick. Such accumulations of material are largely restricted to pre-existing bedrock depressions, such as in the lee of bedrock knobs or in pre-glacial valleys. The latter are especially significant in areas where tributary streams have cut canyons which are transverse to the main direction of ice flow in the region. These transverse valleys act as depositional sinks. They are infilled mainly by basally transported debris when overridden by active ice. Bedrock depressions of this type are very common in the Jasper area and form one of the most significant depositional environments in the region. The stratigraphically complex sequence of glacial sediments discussed in chapter 4 was deposited in the bedrock depression cut by Portal Creek prior to the last major glacial period in the area.

Stratigraphic and provenance studies in the Portal Creek area reveal three major sediment packages of distinct provenance indicating that three separate glacial events may have occurred. However, a detailed facies analysis shows that the oldest two groups of sediment probably were deposited during the same episode. Changes in till provenance are believed to be the result of fluctuations in the dominance of two confluent glaciers originating in different valleys. The facies analysis supports the stratigraphic evidence that the third sedimentary package was deposited in a distinct glacial episode at a significantly

Figure 29: Hypothetical sequence of glacial sediments deposited during a single advance-retreat cycle in a mountain area.


Diamicton Type
Interpretation
6b & 7a - interbedded with sand lenses and layers
- Pre-glacial debris flow deposits
5 - bouldery with normal faulted sand lenses
- Supraglacial tills
3 - banded
- Meltout tills
4 - massive with circular sand lenses
- Englacial meltout tills
1 - massive
- Basal tills
1a - massive with inclined sand lenses
- Lee-side till
1 - massive
- Basal till
1b - massive with plano-convex sand lenses
- Basal meltout till
2 - massive with abundant abraded &embedded clasts
- Lodgement till
6a - intercalated with compressively deformed sands
- Proximal proglacial debris flows
6b - massive with abundant trough-shaped sand lenses
- Distal proglacial debris flows
8/ - fine textured & interbedded with silts & clays/
- Subaquatic debris flows/
7 - coarse textured & interbedded with sands & gravels
- Subaerial debris flows and proximal outwash
- silts& clays/
- Glaciolacustrine sediments/
- gravels
- Glaciofluvial and alluvial fan deposits

later time than the underlying deposits. The erosional unconformity between the second and third sedimentary packages (units 3 and 4 and unit 5, Figure 28) that was probably formed by overriding ice; the presence of both basal and supraglacial till facies above the contact; differences in pebble fabric and lithology; the presence of intervening stratified materials in stratigraphically equivalent deposits in the Astoria River valley; and the presence of weakly developed lateral moraines (the extrapolation of which terminate in the vicinity of the Portal Creek sections); all support the interpretation that the upper-most unit at Portal Creek (unit 5, Figure 28) was deposited during a separate glacial event (a readvance or significant still stand). More research in adjacent valleys is required to assess the regional significance of this event.

Two main sediment associations occur in the Portal Creek area. Sediments interpreted as ice-marginal and supraglacial debris flows were deposited during the advance and retreat of ice in the area (units 1 and 5, Figure 28). The bulk of the sediments at the Portal Creek sections (units 2 to 4, Figure 28) are believed to have been deposited at the base of an active glacier during full glacial times. Genetic varieties of these tills include lodgement, basal meltout, englacial meltout, and subglacial flow tills.

Throughout most of the period of deposition of the basal tills the area was dominated by ice moving generally in a northwest direction. Since the site of deposition was the northeast-southwest trending Portal Creek valley, most sedimentation occurred in a depression transverse or oblique to the direction of ice flow. The narrow width of this depression probably initially allowed for the development of subglacial cavities. These cavities were likely infilled by debris, originating at the glacier sole, slumping and sliding down the lee-side of the bedrock depression (Figure 27). Debris rich basal ice also likely became stranded in the depression and separated, by a shear zone, from overriding active ice. Meltout of the debris-rich ice allowed for the development and preservation of englacial debris bands and stream tunnel deposits. Where ice was actively shearing over previously deposited sediments (or debris-rich ice) individual particles may have been plastered onto the depositional surface resulting in the formation of lodgement till. The progressive upward shift in the position of the shear zone may thus have resulted in alternating deposits of meltout, lodgement and subglacial flow tills, with the latter occurring mainly in the lower part of the sedimentary succession.

Although stratigraphic correlations with dated sediments are tentative, both glacial events recorded in the Portal Creek stratigraphic record are presumed to be Late Wisconsinan in age. Absolute dates were obtained during studies in the Continental Divide area which indicated that no Holocene advance has extended more than one or two kilometers beyond the margins of present glaciers (Luckman and Osborn, 1979; Kearney and Luckman, 1981) and from wood in fluvial sands and gravels underlying a surface till in the Jasper townsite area which yielded a date of 29,100 ±560 (GSC-3792).

It is hoped that the diamicton types designated in this thesis will be applied to farther stratigraphic studies in the Jasper region. The scheme developed should provide a convenient and relevant tool for the field analysis of complex stratigraphic sequences and for regional studies where large numbers of sections must be visited in a short short time. With modifications this scheme may be applicable to other mountain environments and may serve as a basis for the development of other objective approaches to the study of Quaternary sediments.

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Section 83-1 - Jasper Railroad Section

Location: Section 83-1 is located along the C.N. Railroad tracks just north of Jasper townsite at 54° 54' N. and 118° 05' W. of the Sixth Meridian (UTM 278609).

Unit 4a - 0-0.9 m - Diamicton (Type 6a) : sandy silt matrix; clasts mainly granules to medium cobbles, average diameter 1-2 cm, large cobbles and boulders rare; matrix pale yellow (5Y 7/4), surface wash white (5Y 8/2); contains sand lenses (see unit 4b below); well cemented and compacted; clasts sub-rounded to well-rounded, 70-80% quartzite, 5-10% limestone, 10% shale, 5% siltstone; soil development and colluviation in top 0.5 m; roots extend to 1-2 m; lower contact planar and gradational.

Unit 4b - 0.9-3.0 m - Sands and Gravels; fine to medium sands alternating with pebbly sand beds; 40-60% clasts, occasional cobble up to 10 cm in diameter; large scale trough crossbedding (channel-fill crossbedding), crude horizontal laminations, weak planar crossbeds, beds 10-20 cm thick, lens shaped, concave upwards; sands well to very well sorted, pebbly beds poorly to modeately sorted; clasts well rounded, 70-80% quartzite, 10-20% limestone, 10-20% siltstone and shale; lower contact planar and gradational.

Unit 4c - 3.0-5.2 m Diamicton (Type 6a): similar to unit 4a; contains minor sand lenses; similar to unit 4b in the lower part of the unit; small angular inclusions of sand (rip-ups?) occur near the base; lower contact wavy and clear; unit thickens laterally due to local 'scour troughs' (1-5 m wide and 0.5-1 m deep) which appear to truncate unit 3.

Unit 3 - 5.2-6.4 m Medium to coarse sands: pebbles rare; massive, no bedding apparent; light gray color (5Y 7/1-7/2); thins laterally to less than 1 m due to truncation by the overlying unit; lower contact planar to wavy and abrupt to clear.

Unit 2 - 6.4-10.0 m Medium to coarse sands and gravels: fine sand beds rare, gravels mainly small to medium pebbles, maximum diameter about 5 cm; unit generally fines upwards, mainly horizontal bedding with some planar and trough crossbedding; beds 5-30 cm thick; sands well to very well sorted; clasts well to very well rounded; lithologies as in unit 4 above; wood and small gastropod and pelycepod shell fragments found in the lower part of this unit; lower contact partially covered, otherwise planar and abrupt.

Unit 1 - 10.0-19.8 m Sandy gravel: medium sands to small cobbles; most clasts pebble to small cobble sized; clast supported; unit fines upward; graded horizontal bedding; poor to well sorted; a few thin (5 cm) beds of sand are very well sorted; lower contact covered.

Section 83-2 - Jasper Water Supply Road Section

Location: 52° 53' N. and 118° 06' W.of the 6th Meridian (UTM 254583). This section is about 100 m up the Jasper townsite water supply road on the northwest side of town.

Unit 6 - 0-4.5 m depth Diamicton (Type 1): silty sand matrix; 30-40% clasts, mode 10-2 cm, largest 0.5 m diameter; pale yellow (5Y 7 / 4), surface wash white (5Y 8 / 2); massive, unstratified; unsorted; weakly compacted, moderately cemented; clasts subrounded to well rounded, 85% quartzite, 10% pebbly conglomerate, 5% limestone; laterally to the southeast this unit thickens to 10+ meters; to the east this unit grades into unit 5 and in the transition zone shows a weak stratification of the same orientation as gravel strata in unit 5 (Dip 30-35°, dip direction 20°; the top 0.5 meters of this unit are colluviated; lower contact planar and abrupt, dips at about 25° to the south - southeast truncating bedding in underlying units.

Unit 5 - 0-4.5 m depth (lateral equivalent of unit 6) **Fine to coarse sands and gravels:** unit contains mainly medium to large pebbles; total clast content 80%; pale yellow (2.5Y 7 / 4) to dusky red or very dark grey (2.5 YR 3 / 2); gravels show large scale planar crossbedding, steely dipping (30-35°), apparent dip direction 20°; sands show small scale planar cross-laminations; large and abrupt changes iin grain size and sorting from bed to bed; slight coarsening upward; the basal meter consists of well sorted, pale yellow (5Y 7 / 3) horizontally laminated silts grading upwards into horizontally stratified medium to coarse sands with some gravel lenses up to 1 cm thick with pebbles up to 5 cm in diameter, grading upwards into a bed of matrix supported small to large cobbles which become clast supported within 10-20 cm; gravels poorly to moderately well sorted; poorly cemented and compacted; clasts well to moderately well rounded; 65% quartzite, 20% shale, 5% sandstone, 7% pebbly conglomerate, 2% limestone, cobble sized clasts nearly all quartzites; clasts frequently fractured; unit grades laterally into unit 6 in the west and to the east into similar materials but with opposing dips (dip 45°, dip direction 150°), slumping of these gravels has disturbed the eastern part of the section but in a small exposure on the far eastern edge of the section horizontal boulder beds, which occur at the same level as units 1 and 2, are visible); lower contact clear and planar.

Unit 4 - 4.5-9.5 m Medium to coarse sands and cobbly gravels: similar to unit 1 except: mainly medium to coarse sands in lower part of unit and very coarse sands in top part; abundant scour and fill structures with lag gravels up to cobble size (maximum clast diameter about 20 cm); lower 20 cm of unit consists of very well sorted fine sands with type A and type AB-transitional climbing ripples; generally coarsens upwards; small and large scale planar cross-bedding common.

Unit 3 -19.5-15.7 m Fine to coarse sands and pebbly gravels: gravels mainly granules to medium pebbles, some large pebbles; gravels both matrix and clast supported; small to large scale planar and tough cross-bedding common; average bed thickness 5 cm; unit generally fines upwards; top several centimeters of unit are well sorted fine sands which grade into hoizontally laminated silts; pebbles up to 30 mm in diameter occur in the upper part of the capping silt bed; gravels generally poorly sorted, silt and sand beds moderately to very well sorted; poorly cemented and compacted; clast lithologies similar to unit 1; inclusions of poorly sorted diamicton are the result of colluvial infilling of recent fractures; lower contact gradational and planar.

Unit 2 - 15.7-18.9 m Sands and gravels: similar to unit 1 except: sand beds common; some large scale trough crossbeds present; unit coarsens upwards in the lower meter and then fines upwards as in unit 1; dish structures are prevalent in a basal sand bed (60 cm of moderately to very well sorted, medium to coarse sands); wood fragments found in a 3 cm thick pebble bed at a depth of 17.9 meters (1120 m asl) provided a date of 29,100 ±560 years BP (GSC-3792); 1 gastropod and shell fragments were also collected from this bed; capping silts are loaded into the underlying sands (silt balls) and locally contain up 50% granules and small pebbles;

lower contact clear and planar.

Unit 1 - 18.9-22.5 m Sandy gravel: gravels up to 9 cm in diameter, average 1 cm; gravels imbricated (generally dip to the south-southwest (200°) and clast supported; matrix mainly medium to coarse grained sands; minor sand and silt lenses and beds up to 4 cm thick; sands olive (5Y 5 / 3), silts pale yellow (5Y 7 / 3); large scale horizontal bedding (dip 10°, dip direction 240°, average bed thickness 40 - 80 cm; occasional small to large scale planar cross bedding in sands; unit fines up with mainly sandy beds in top meter; unit capped by a few centimeters of sandy silt with some granules in the lower part and with horizontal wavy laminations; gravels poorly to well sorted, sands and silts moderately to very well sorted; poorly cemented and compacted; clasts are rounded to subangular, 55-65% quartzite, 3-5% sandstone, 15-20% pebbly conglomerate, 3-5% phyllite, 10-15% shale; limestone rare; injection structures common; silt beds sometimes extend laterally for tens of meters before pinching out; lower contact covered.

Section 83-4 - Upper Jasper Water Supply Road Section

Location: Section 83-4 is located just upvalley from section 83-2 along the Jasper water supply road (52° 83′ N, 118° 06′ W - UTM 252585).

Unit 8 - 0-1.0 m Diamicton (types 5, 1): matrix sandy; unit largely colluviated; weak to no reaction to HCL; about 20% clasts, subrounded to subangular, maximum diameter 1.5 m; clast lithologies about 50% quartzitic sandstone, 20% other sandstone, 20% shale, 5% phyllite, 5% pebbly conglomerate, occasional metamorphic erratic (mica-garnet schist); lower contact wavy and diffuse.

Unit 7 - 1.0-2.0 m Fine sands and silts laterally interbedded with diamicton (type 8): sands slightly gravelly, similar to unit 1; silts olive yellow (2.5Y 6/4); horizontal and irregular laminations; sand beds up to 0.25 m thick; occasional clasts up to 0.25 m in diameter; the number of clasts within individual beds increases laterally to where the unit grades into matrix supported diamicton similar to unit 8; unit thickness also increases laterally (towards the valley center) up to two meters; lower contact wavy and clear.

Unit 6 - 2-15 m Gravelly diamicton (type 7b): matrix silty to sandy; 90% clasts, maximum diameter 0.5 m, average 2-5 cm; crude horizontal stratification; beds 0.2 to 3 m thick; moderately to very poorly sorted; poorly cemented, moderately compacted; moderate reaction to HCL; clasts subrounded to well rounded, occasionally striated, lithologies similar to unit 2 except up to 20% limestone; unit thickness varies from about 8-14 m; lower contact planar and clear.

Unit 5 - 15-19.5 m Sands interbedded with gravelly diamicton (type 7b): mainly fine to medium sands with some gravelly sands; gravelly diamicton beds less common and generally less than one meter thick; sands exhibit large scale trough and planar crossbedding, horizontal bedding, planar laminations and ripple bedding; sands very well sorted, gravelly sands moderately to poorly sorted; gravelly diamicton beds similar to unit 6; contacts between diamicton and sands are sharp and erosional; beds have an overall dip of 5° and dip direction of 315°; unit largely covered by slumping; lower contact generally smooth and clear to abrupt.

Unit 4 - 19.5-22.0 m Gravelly diamicton (type 7b)interbedded with sands: mainly gravelly diamicton beds similar to unit 2 below; sands similar to unit 3 below; gravel beds increase in thickness from 15-25 cm near the base to over 1 m near the top of the unit; sand beds mostly about 5 cm thick; general dip and dip direction of beds same as unit 5 above; lower contact smooth and clear to abrupt.

Unit 3 - 22-25 m Fine to coarse sands: medium to coarse sands, light gray in color (2.5Y 7/2), silts and fine sands light yellowish brown (2.5Y 6/4); well developed planar laminations and ripple laminations (types A and B ripple-drift cross lamination and sinusiodal ripple lamination); beds two to several centimeters thick; general bedding dip 4-6° and dip direction 310°; individual crossbed dips as high as 27° (27°, 276°) and as low as 1° (1°, 96°) were recorded; lower contact planar and abrupt.

Unit 2 - 25-27.5 m Gravelly diamicton (type 7b): mainly pebbles to small cobbles; maximum clast diameter about 20 cm; matrix mainly medium to coarse sands, some silts and clays; mainly clast supported; crude inclined planar stratification and possible (weak) crossbedding and scour surfaces; bed thickness 5-50 cm; bedding dip and dip direction variable - averages 5° and 315° respectively; moderately to very poorly sorted; clasts subrounded to well rounded, 60-75% quatzitic sandstone, 5% other sandstone, 5-15% dolomite and argillaceous limestone, 5% pebbly conglomerate, 5% shale; strong reaction to HCL; lower contact partially covered, otherwise planar and abrupt.

Unit 1 - 27.5-29.0 m Gravelly sands: mainly medium to coarse sands with some gravelly sands; clasts up to medium pebble size; sands olive yellow to light olive brown (2.5Y 6/6 to 5/4); small to large scale trough and planar crossbeds, horizontal laminations, some scour and fill structures; bed thickness 1-15 cm; mainly moderately to well sorted but pebbly beds are poorly sorted; no reaction to HCL; clasts subrounded to well rounded; lithologies as in unit 2 above; lower contact covered.

Section 83-5 - Rocky River Section

Location:Rocky River Valley - approximately 8 km from Highway 16 NTS 83 F / 4 W, 53° 06′ N, 117° 54′ West of the 5th Meridian (UTM - 11UMJ 400839).

Unit 5 - 0-2 M - Sands and silts: silts 2.5Y 5 / 3, sands 2.5Y 4 / 4; horizontally stratified; beds generally about 2 cm thick but sand beds up to 20 cm thick; silts mottled but show weak laminations; minor small scale cross bedding in sands; pebble layers locally present; lower contact sharp and planar in places, slumped elswhere.

Unit 4 - 2-15 M - Diamicton (types 4, 6a, 6b): Matrix texture variable - generally sandy or silty sand; (10YR 5 / 2); matrix supported; clasts granules to small cobbles, maximum diameter about 50 cm, mainly small to large pebbles, locally up to 80% pebbles and larger; total clast content 35-40% massive with minor sand lenses and layers; poorly sorted to unsorted; poorly to moderately cemented; clasts subangular to rounded; clasts striated and pitted; 50% carbonates, 35% quartzitic sandstone, 10% siltstone and shale, 5% pebble conglomerate; larger clasts dominantly sandstones; lower contact gradational.

Unit 3 - 15-23 M - Diamicton (type 1): matrix sandy silt and becomes more clay rich towards the base of the unit; matrix supported; unsorted; clasts mainly small to large pebbles (few cobbles and very large pebbles); clasts commonly striated; clast lithology and shape as in unit 4; lower contact covered due to slumping in the clay rich lower part of the unit.

Unit 2 - 23-26 M - Silts and clays: 2.5Y / 7 to 2.5Y / 8; very well sorted; no clasts observed; some horizontal laminations and beds (102 cm thick) present; minor sand lenses (4 cm thick) near the base of the unit; lower contact sharp and planar.

Unit 1 - 26-70+ M - Gravels and sands: interbedded sand, pebbly gravel and cobbly and bouldery gravel beds; prominent boulder beds at base of unit and at depths of about 35 and 45 m; bed thickness generally about 0.2 m but up to 1 m; dominantly horizontal bedding with some trough crossbedding and scour and fill structures; cross bedded sand lenses up to 0.6 m thick common in gravel beds; sands and pebbly gravels mainly moderately to well sorted; cobble and boulder beds mainly poorly sorted; lower contact sharp and irregular - the gravels have eroded deeply into the underlying shale bedrock leaving an unconformity with many meters of relief.

Section 82-10 - Roche Miette Section

Location: Section 82-10 is located along an unnamed, intermittent creek draining off the north side of Roche Miette - NTS 83 F/4 W, 53° 11' N., 117° 57' West of the 5th Meridian, (UTM 11UMJ 363928). The section is accessible via a pipeline right-of-way which intersects Highway 16 about 5 km north of the Rocky river bridge (3.5 km west of Pocahontas).

Unit 4 - 0-1.5 m Silts and fine sands: variable coloration (red, white, brown); weak horizontal bedding; buried soil horizons (Ah layer) and ash layers are present and conform to the topography; unit thickens laterally to depths of two meters or more.

Unit 3 - 1.5-3.0 m Gravels: mainly small pebbles to small cobbles; some medium to coarse sands and granules; some very large clasts up to 3 m long; modal clast diameter about 5 cm; bedding disturbed or obscure in most places; Disruption is mainly compressive in nature (folds and low angle (thrust) faults) and strongest below large clasts; most beds moderately to well sorted but some are poorly sorted; clasts mainly rounded to well rounded, large clasts mostly subangular; abundant striations, especially on the upper surface of large boulders (striations and the long axis of large boulders parallel the main valley); clast lithology similar to unit 2 below except for minor metamorphic erratics (mica-garnet schist and muscovite-biotite gneiss) on the surface; unit thickness varies from 0-3 m; lower contact gradational.

Unit 2 - 3-10 m Gravels: granules to cobbles, modal diameter about 5 cm, some medium to coarse sands; large scale planar and trough crossbedding and horizontal bedding, dip 1.5° - 3°, dip direction 35° - 71° (parallel to the main valley); moderately to well sorted; poorly cemented; $CaCO_3$ coating on most exposed pebbles gives unit a whitish color; clasts rounded to well rounded; 40-50% quartzitic sandstone, 40-50% limestone, 10% siltstone, 5% pebbly conglomerate; up to 90% of large pebbles and cobbles are quartzitic sandstone; unit thickness varies from one to nine meters; lower contact clear and wavy.

Unit 1 - 10-50+ m Diamicton, gravel, sand and silt: fine sands to large cobbles, maximum clast diameter about 2 m; weak large scale planar and trough cross-stratification; bed thickness 2 cm to 1 m but generally 10-20 cm; beds dip 3° to 9° to the northeast (305°); sand and pebble beds are mainly well sorted, gravel beds with larger clasts are generally moderately to poorly sorted; diamicton beds, common in the upper part of the unit, are very poorly sorted and are mainly clast suported; very poorly sorted diamictons with numerous large clasts dominate this unit in more southeasterly (upvalley) exposures; minor iron-stained open-work gravels near the base of the unit; clasts are angular to rounded but mainly subangular to subrounded; roundness increases with sorting; striations absent; clasts nearly 100% of local lithology (mainly limestone and dolomite), sandstone and quartzite rare, minor argillaceous limestone.

Section 83-11 - Jacques Creek Section

Location: NTS 83 E/ 1 - 53° 03′ N, 118° 02′ West of the 6th Meridian (UTM 308783). about 2 km from Highway 16 along the northeast side of Jacques Creek.

Unit 4 - 0-3 m - Interbedded gravel, sand and diamicton (type 6b); gravels mainly clast supported, clast content 60-90%, maximum diameter 1.5 m; gravels are planar and trough cross stratified, beds up to 0.5 m thick; sands and minor silts exhibit horizontal laminations and small scale planar cross bedding; cross beds dip 2-3° towards 285°; gravels poorly to moderately sorted, diamicton very poorly sorted, sands and silts well sorted; clasts rounded to angular, mainly subangular; 50% limestone and dolomite, 20% shale and siltstone, 30% sandstone, minor chert and pebbly sandstone; few clasts striated; lower contact gradational but locally represents a sharp scour surface into unit 3 (scours 3-5 m wide and 1-2 m deep).

Unit 3 - 2 -25 m - Diamicton (types 2, 3, 4): sandy silt matrix, pale yellow (2.5 Y 7 / 4); total clasts generally 30-60% but higher in the lower part of the unit; average clast diameter 1-2 cm, maximum 1 m except at the base where a relatively large number of cobbles and boulders up to 3 m in diameter occur; weak horizontal bedding is apparent due to differences in color and grain size distribution between beds; in the lower part of the unit there is a bed about 2 m thick with up to 80% subangular limestone clasts and little matrix; in the middle of the unit there are horizontal bands of silty diamicton (type 3), 10-20 cm thick, with 5-10% clasts; one bed in the upper part of the unit is comprised of a very poorly sorted boulder rich diamicton 0.5 m thick; lenses of moderately to well sorted medium sands to pebbles occur locally; lenses size varies from 3-10 cm thick and 3 cm to 2.5 m wide; irregular inclusions of porous poorly sorted gravels (mainly subangular to angular cobbles with a granule to pebble matrix) occur in the lower part of the unit; matrix reacts strongly to HCL; clasts 50% limestone, 10% dolomite, 30% quartzite and quartzitic sandstone, 5% siltstone and minor shale, pebbly sandstone and chert; clasts mainly subangular to rounded with quartzites exhibiting the highest rounding; limestone clasts frequently fractured and heavily striated particularily in the lower part of the unit where the diamicton (type 2) is almost clast supported in places; the lowest few meters of the unit are partly covered but some exposures show diamicton with lenses or beds of very well sorted medium sands, well sorted granules and poorly sorted gravelly sands; due to the partial cover it was not possible to determine the shape of all lenses but some were clearly circular in cross section (type 4); sorted materials may locally be interbedded with diamicton; lower contact covered.

Unit 2 - 25-30 m - Silts and sands; sands mainly fine to very fine; color pale brown (10YR 6/3) to olive yellow (2.5Y 6/6); light grey (2.5Y 7/2) on weathered surfaces; weak horizontal bedding, beds 2-4 cm thick, finer laminations also faintly visible; lower contact clear, wavy.

Unit 1 - 30-50+ m - Gravelly diamicton; matrix mainly sands and granules, some silt; pale brown (10YR 6/3); 80-90% total clasts, mode 2-3 cm, maximum 0.5 m, mainly clast supported; weak horizontal bedding inclined downvalley; generally poorly sorted with some moderately sorted gravel beds; no striated clasts observed; 50% limestone, 30% dolomite, 10% sandstone, 5% siltstone, 5% sandy limestone, minor tufa and pink quartzites; quartzites are moderately well rounded; lower contact covered.

Section 83-18 - Pocahontas Warden Station

Location: Section 83-18 is located just south of Highway 16 above the abandoned Pocahontas coal mine (NTS 83 F/4, 53° 12′ N, 117° 56′ W of the 5th Meridian, UTM 381946).

Unit 13 - 0-7 M - Diamicton (types 1, 5): color brown (10YR %/3), light grey on weathered surface (2.5Y 7/2); silty matrix; total clast content 40-50%, average size 1-2 cm, maximum diameter 0.5 m; massive (type 1); matrix supported; unsorted; weakly cemented and poorly compacted; strong and rapid reaction to HCL; clasts subangular to rounded; striations abundant; 60-70% limestone, 10-20% quartzite, 10% sandstone, 10% siltstone; metamorphic erratics occur in the upper part of the diamicton (type 5); the surface of the section has been disturbed by a bulldozer; unit varies in thickness from 2 to 8 meters; lower contact sharp and erosional and truncates bedding in unit 12, contact dips at an angle of 8° to the southeast(117°).

Unit 12 - 7-14 M - Gravels and sands: gravels mainly medium pebbles to large cobbles; horizontally stratified and planar cross-stratified; beds dip 1-2° to the NW (297°); moderately to well bedded; sands light brownish gray in color (2.5Y 6/2); sand lenses are up to several meters wide and 0.5 meters thick, horizontally laminated; some sand lenses exhibit well developed trough (channel fill?) cross laminations; gravel beds up to 2 m thick; poorly to moderately sorted; some well sorted gravel beds present; clasts moderately to well rounded; 60-70% limestone, 20-30% quartzitic sandstone, 10% other sandstone, 10% siltstone, minor pebbly conglomerate, red dolomite, and shale; unit varies in thickness from 3-7 m due to truncation by unit 13; lower contact gradational.

Unit 11 - 14-20 M - Gravels and sands: same as unit 12 except beds dip at angles up to 7° in various directions; some gravel beds iron stained; 40-60% limestone, 30-40% quartzitic sandstone, 10% other sandstone, 10-15% siltstone, minor ironstone, pebbly conglomerate and shale; lower contact gradational.

Unit 10 - 20-38.5 M - Gravels and sands: same as unit 11 except gravels are mainly horizontally stratified; iron stained gravel beds less common; sand lenses mostly horizontally laminated and 10-40 cm thick; lower contact gradational.

Unit 9 - 38.5-40.5 M Sandy gravel: dominantly medium pebbles to small cobbles with a fine sand matrix (stained to a dark yellowish brown color - 10YR 3/6); horizontal bedding; beds 10 to 40 cm thick, poorly to moderately stratified with gradational contacts; poorly to moderately sorted; clasts subrounded to well rounded, subangular clasts rare; 40-60% limestone, 30-40% quartzitic sandstone, 10% other sandstone, 10-15% siltstone, minor ironstone and shale; lower contact covered.

Unit 8 - 40.5-44.5 M - covered

Unit 7 - 44.5-46.1 M - Diamicton (type 7a): massive; silty sand matrix brown in color (10YR 5/3), light grey when weathered (2.5Y 7/2); average clast diameter 1-2 cm, maximum 0.5 m; matrix to clast supported; 40-60% total clast content; unsorted; weakly cemented; poorly compacted; strong, rapid reaction to HCL; clasts subangular to rounded, commonly striated; 60-70% limestone, 10-20% quartzitic sandstone, 10% other sandstone, 10% siltstone; lower contact undulatory and clear.

Unit 6 - 46.1-47.5 M - Gravels and sands: same as unit 1 but well sorted gravels and iron stained beds absent; sand lenses 5-10 cm thick; lower contact horizontal and conformable with unit 5.

Unit 5 - 47.5-51.7 Sandy gravel: same as unit 9 except beds are dominantly poorly sorted and vary from 0.2 to 1.5 m in thickness; base of unit is coarser grained, basal 0.5 m consists of boulders up to 1 m in diameter; lower contact erosional (sharp and slightly wavy - scoured?).

Unit 4 - 51.7-52.3 M Sands and silts: mainly fine sands; silt beds less common; sands olive brown (2.5Y 4/4) in color, commonly stained to a yellowish brown (10Y 5/6); silts olive grey (5Y 4/2); mainly massive but horizontal beds from 1 to several cms thick are locally apparent; faint horizontal laminations also present; silt beds up to 2 cm thick; unit is wedge shaped and pinches out laterally in about 8 m. lower contact erosional.

Unit 3 - 52.3-54 M Gravelly diamicton (type 7b): matrix sandy, dark greyish brown in color (2.5Y 3/2), weathers to light olive brown (2.5Y 5/4); 40-70% total clasts; all sizes up to 0.5 m diameter, mode about 5 cm; mainly clast supported; crude horizontal stratification in some beds, due to high matrix concentrations (up to 80% in places); beds dip 5° to the NW (327°) (ie. towards the valley center); tabular clasts tend to lie flat giving the unit a weak imbrication; poorly to unsorted; strong, rapid reaction to HCL; clasts subangular to angular, rounded clasts uncommon; striations rare; 40-60% sandstone, 30-40% limestone and dolomite; 10% siltstone, 10% quartzitic sandstone, 5% shale (almost entirely local rocks); lower contact sharp and planar where not disturbed by slumping.

Unit 2 - 54-55.5 M - Sands and silts: same as unit 4 except unit is tabular; small scale faults and distortion of bedding (probably due to slumping); lower contact indistinct and slighty wavy; contact slopes towards the valley center.

Unit 1 - 55.5-57.5 M Gravelly diamicton: same as unit 3 except total clast 40-60%, rounded clasts rare and striated clasts absent; lower contact covered.

Section 83-28 - Pocahontas

Location: 1.5 km from Highway 16 up the road to Miette Hotsprings just above Punchbowl Falls (NTS 83 F/4 W, 53° 12′ N, 117° 55′ W of the 5th Meridian, UTM 388947).

Unit 3 - 0-2.8 M - Silts and clays: clayey silt texture, color grey; horizontally laminated; abundant gastropods; unit thickness varies from 1-5 m; the top 1-2 m locally are massive sandy silts which show buried soil (Bf, Ah?) horizons; grades laterally into poorly exposed matrix supported diamicton (type 1?); lower contact planar and conformable.

Unit 2 - 2.8-4.1 M Gravels: mainly small pebbles to small cobbles; planar and trough cross-stratified; dip 16-25°, dip direction 10-60°; some sand lenses; well to very well sorted; beds commonly iron stained; clasts well rounded; 60-70% limestone, 10% quartzitic sandstone, 10% dolomite, 5-10% siltstone, minor pebbly conglomerate, other sandstone and shale; clasts dominantly of local lithology; towards the NW (towards the main valley) this unit thickens to 10+ m and the upper part grades into a poorly exposed diamicton containing striated clasts of similar lithology to those listed above.

Unit 1 - 4.1-8.4 M Gravelly diamicton (type 7b): matrix silty sand; clasts up to small cobble size, no boulders; 70-80% clasts; massive; poorly sorted to unsorted; clasts mainly subangular to angular; 60-75% limestone, 20-25% sandstone, minor siltstone, quartzitic sandstone and dolomite; unit thickens to 5 m or more laterally (to the SE); lower contact covered.

Section 83-29 - Portal Creek Composite Section

Location: NTS 83 D/ 16 52° 47' N, 118° 04' W of 6th Meridian (UTM 11UMJ 278486) Approximately 10 km south of Jasper townsite on road to Marmot Basin ski area - about 200 m southeast of Portal Creek bridge.

Unit 5 - 0-9 m - Diamicton (types 1, 5 and 6); pale yellow(5Y7 / 4); silty sand matrix(53% sand, 29%silt); 10-20% clasts (40% pebbles, 30% cobbles, 30% boulders); boulder content noticeably higher than in underlying unit (type 5); maximum clast diameter about 5 m; mainly massive and unstratified; ripups from the underlying diamicton and minor sand lenses, generally about 10-20 cm thick and 3-5 m wide occur in the lower part of the unit (type 6); moderately cemented and compacted; clasts subangular to well rounded; all boulders are quartzitic sandstones; few clasts striated; lower 1-2 m of unit are locally enriched in shales with numerous striations (type 1); unit pinches out to the east (downvalley); lower contact wavy and clear to gradational.

Unit 4 - 9-40 m - Diamicton (types 3, 1, 1a); olive gray(5Y5 / 2); matrix muddy (35-45% sand, 20-35% silt); clasts mainly pebble sized; boulders rare; mainly massive and unstratified (type 1); diamicton occasionally shows color banding in the upper portion (type 3); one olive colored band (5Y6 / 2 to 5 / 6), occurring about 4m below the contact with unit 5, is 6-12 cm thick and is laterally traceable in a slightly undulating horizontal plane for several meters; bands are locally depleted in silts and clays with up to 60% clast content (average 25%); inclined sand lenses dipping towards the valley center (north are locally present (type 1a); strongly compacted; clasts sub-angular to rounded; cobbles and boulders all quartz sandstones and quartzites; lower contact gradational.

Unit 3 - 40-60 m - Diamicton (types 1, 1b and 4); similar to unit 4 except diamicton locally contains sand and gravel lenses (type 1b) and pods (type 4); lenses are generally 20-40 cm thick and 2-3 m long; pods are more circular with diameters of about 1 m; upper surfaces of pods and lenses vary from planar to strongly convex upwards, lower surfaces are planar to concave upwards; contacts with the surrounding diamicton are generally sharp and smooth to irregular; lenses generally have better sorting, better preserved bedding structures and are sandier than pods; trough crossbeds are the main sedimentary structures; large clasts frequently protrude into the sands and gravels from the upper contact; occasional inclusions of diamicton and anomalously large clasts occur within the sands and gravels; bedding is generally deformed and faulted; large changes in grain size occur over short distances in some beds; paleocurrent directions mainly to the north (340°-40°); lower contact of unit gradational.

Unit 2 - 60-80 m - Diamicton (types 1 and 2); olive yellow (5Y6/6); matrix sandy to silty (highly variable); 30-40% total clasts; clast diameter up to 5 m, average 10 cm; massive, compact and unstratified; clasts show a strong fabric orientation between 90° and 100°; abundant boulder sized shale clasts in upper part of unit; clasts angular to subrounded, mainly subangular; small plano-concave sand lenses occur locally, especially near the base of the unit; clast size decreases and clast content increases in the lower half of the unit; unit pinches out or is covered to the east; lower contact gradational.

Unit 1- 80-95+ m - Diamicton (type 6) intercalated with silts sands and gravels; dominantly (80%) diamicton occuring as both lenses and beds from 1-10 m thick; sand and silt lenses occur frequently and are generally about 0.5 m thick and 1-3 m long; some large sand and gravel beds, traceable for up to 10-15 m, occur; they are 2-3 m thick and composed of silt beds (average 1 cm thick), granular sand beds (average 2-4 cm thick) and pebble beds (average 10-15 cm thick) which dip at various angles and often are distorted; apparent dip and dip direction are 10° and 32°, respectively (parallel to Portal Creek);
Diamicton (types 6a and 6b): olive (5Y5/6); variable texture, mainly silty sand to sandy silt; 20-80% total clast content; generally massive although stringers, lenses

and irregularily shaped pods of coarse sands and gravels are locally common (type 6b); some possible flow folds present; poorly cemented; clasts mainly subangular to subrounded; few striations;

Silts, sands and gravels: very well sorted to poorly sorted; clasts up to large pebble size frequently occur within sand and silt beds; primary sedimentary structures are rare and usually only faintly preserved (mainly wavy and planar laminations); beds are frequently highly contorted, folded and faulted and are often intercalated with thin beds of diamicton (type 6a); load structures, injections, fluid escape structures, clay inclusions and deformed laminations are common; sand and gravel lenses near the top of the unit show the greatest deformation and locally appear sheared and faulted; apparent dip and dip direction are 10° and 32°, respectively (parallel to Portal Creek); the amount of sand and gravel relative to diamicton increases dramatically downvalley (to the NE), sand lenses also are larger and more abundant, diamictons become sandier and have much higher total clast contents, gravel beds increase in frequency, striated clasts become rarer, and limestone contents increase to the NE; lower contact of unit covered.

Appendix 2a: Results of Grain Size Analyses - Sieve data - Bulk textures (<16mm)

Sample # (by diamicton type)	% small to medium pebbles (4-16 mm)	% granules (2-4 mm)	% sand (.0625-2 mm)	% silt and clay (<.0625 mm)
Type 1				
82-2-1	33	7	33	27
82-2-2	21	6	47	26
83-7-1	18	8	29	45
83-7-1a	19	6	31	44
83-18-13	20	3	37	40
83-13-5	20	5	30	45
Type 2				
83-11-3	23	9	29	39
83-11-3d	13	8	34	45
83-27-3a	13	5	31	51
83-10-1	10	2	39	49
Type 3				
83-29-w4b	17	6	28	49
83-29-w4	13	5	29	53
Type 4				
83-29-4m	11	5	41	43
83-29-4	23	5	42	30
83-11-3b	10	7	31	52
83-15-7	39	4	29	28
Type 5				
83-7-3	20	16	38	26
83-8-1	21	10	32	37
82-34-2b	10	5	38	47
82-34-2a	12	6	40	42

82-27-1	19	9	44	28
82-29-w5	20	7	34	39
Type 6				
83-6-2	9	3	59	29
83-12-2	16	6	52	26
83-17-7a	24	12	45	19
83-6-3	21	5	52	22
82-33-3	13	6	32	49
82-27-3b	19	6	40	35
83-29-w1	17	6	32	45
83-44	22	4	53	21
83-15-5	22	5	53	20
83-42	24	5	49	22
Type 7				
82-17-7g	47	18	33	2
82-17-7be	41	18	32	9
83-40	72	5	21	2
83-8-2	44	17	32	7
82-17-7b	52	24	17	7
83-7-2g	29	28	31	12
83-7-2	50	15	34	1
83-11-4	45	14	36	5
83-41	54	9	23	14
Type 8				
83-15-4	24	2	34	40
83-13-3b	18	5	66	11
Non-glacial				
83-18-7	39	5	27	39
82-11-3	60	10	15	15
83-29-4g	44	27	29	0

Appendix 2b: Results of Grain Size Analyses - Hydrometer data - Matrix textures (<2 mm fraction)

Sample #	% Crs. sand	% Med. sand	% F. sand	% Silt	% Clay	Mean (phi)	Sorting (phi)	Skewness (phi)
Diamicton								
Type								
Type 1								
82-2-1	25.8	11.2	13.0	24.3	25.7			
82-2-2	14.8	11.0	15.7	23.6	34.9			
83-7-1	15.8	12.2	26.8	34.9	15.3	4.3	3.4	-4.0
83-7-1a	16.0	8.6	14.4	33.5	27.4			
83-18-13	17.0	9.3	13.8	32.1	27.9			
83-15-5	9.4	11.4	26.6	28.2	24.6	5.0	3.7	-3.2
83-13-5	10.0	8.0	21.9	32.3	27.8			
83-5-3	12.6	10.8	11.5	33.3	26.9	5.4	4.1	-4.3
83-43-7	18.2	11.0	18.8	28.9	23.1	5.1	4.4	-3.8
Type 2								
83-11-3	15.2	8.4	19.2	33.2	24.0			
82-27-3a	11.0	10.4	20.1	33.5	23.5			
83-10-1	13.6	10.4	20.6	30.9	24.5			
Type 3								
83-29-w4	18.7	10.0	15.0	23.3	33.0			
83-29-w4b	13.3	7.2	15.3	30.2	34.0			
83-5-3b	22.2	7.2	7.8	29.0	32.6			

Type 4								
83-11-3b	11.6	8.8	16.4	32.2	31.0			
Type 5								
83-7-3	30.2	12.4	17.0	23.8	16.6	3.7	4.1	-2.4
83-43-7	9.9	10.2	25.8	34.1	20.0	5.0	3.6	-3.7
83-34-2b	10.4	10.0	23.8	26.3	29.4			
83-34-2a	13.6	10.0	23.2	30.1	23.1	5.0	4.1	-3.5
82-27-1	22.4	14.8	26.8	24.3	11.7	3.6	3.4	-2.8
83-29-w5	18.6	9.6	21.8	30.1	19.9	4.4	3.9	-3.5
83-4-13	15.6	11.5	24.9	33.8	14.2	4.2	3.3	-3.8
82-11-2	3.3	9.3	41.2	26.9	19.4	5.0	3.3	-2.7
Type 6								
83-6-2	9.2	18.4	39.2	23.3	9.9	3.6	2.6	-3.2
83-13-2	16.5	11.9	27.4	37.2	7.1	3.7	2.9	-3.8
82-17-1a	43.1	13.6	13.8	17.4	12.6			
83-6-3	16.2	21.0	32.7	19.7	10.4	3.4	2.8	-2.8
82-2-3	21.2	12.0	21.8	27.7	17.3	4.1	3.9	-3.0
82-33-3	17.2	12.8	22.0	24.3	23.7	4.7	4.3	-2.9
82-27-3b	16.4	13.4	23.4	26.9	19.9	4.5	3.9	-3.0
83-10-6	8.6	5.8	37.2	38.2	10.3	4.3	2.3	-4.3
83-2-11	18.2	18.6	19.5	24.4	19.3	4.2	4.0	-2.3
Type 7								

83-8-2	51.0	16.8	13.2	9.0	10.0			
82-17-1b	55.8	8.0	8.9	13.6	13.6			
82-17-b	55.8	14.3	8.9	17.4	13.6			
83-7-2g	48.8	11.0	11.6	15.8	12.9			
83-4-1	53.2	9.0	4.1	17.1	16.6			
Type 8								
83-13-3b	5.6	11.0	47.2	21.0	15.2	4.3	2.9	-2.7
82-27-3L	15.2	12.2	24.9	31.3	16.6	4.4	3.6	-3.2
Non-glacial								
82-11-3	25.8	11.2	13.0	24.3	25.7			
83-18-1	16.2	13.6	21.4	29.7	19.0	4.5	3.8	-3.2
82-10-1	46.2	15.2	12.8	14.3	11.6			

Appendix 3: Results of Lithologic Analyses

Sample #	% Sandstone	% Pbly. ss. and congl.	% Shale	% Siltst. and mudstone	% Lst.	% Dolst.	% Other
83-29-5w	48	4	26	12	6	2	2 chert
83-29-5s	68	8	20	4	-	-	
83-29-5x	68	2	10	8	6	6	
83-29-5o	62	4	22	10	-	2	
29-1t	58	10	22	9	1	-	
29-5t	46	2	40	12	-	-	
29-5p	48	-	24	26	-	2	
29-4/5	50	4	30	8	6	2	
83-29-4b	50	6	36	6	2	-	
83-29-4	40	-	34	8	14	4	
83-29-4c	48	2	34	14	-	2	
83-29-4x	58	-	6	4	22	10	
83-29-4d	46	2	18	10	16	8	
29-2t	30	12	24	20	10	4	
83-29-4s	54	2	12	16	10	6	
29-4m-lp	48	2	42		4	4	
29-4sp	55	-	31		8	5	1 chert
29-4com	53	1	34		7	5	
29-4sp2	54	-	32		6	6	2 chert
83-9-3gp	56	-	30		10	4	

83-9-3	46	2	8	12	20	12	
83-9-4	56	2	6	14	16	6	
29-4m	40	-	48		8	4	
83-29-m	30	34	160	10	6	4	
83-29-g	76		24				
83-29-E2	58	2	34		2	4	
83-29-1	60		40				
83-29-W1	72	4	14	10	-	-	
83-29-FEG	48	24	12	6	8	2	
83-9-1	60		18	20	-	2	
83-29-5ave	64	6	18	8	2	2	
83-29-4ave	46	4	21	9	14	7	
83-29-3ave	47	1	38		9	5	
83-29-2ave	66		29		2	3	
83-29-1ave	65		34		-	1	
83-29-3,4	50		32		12	6	
83-29-1,2,5	67		30		1	2	
83-7-3	38	34	14	4	4	4	2 schist
83-7-2	24	48	12	8	-	8	
83-7-1	62	18	8	4	-	8	
83-8-1	54	30	8	-	tr	tr	8 schist
83-8-2	42	32	12	8	6	-	

83-10-1	50	tr	4	4	40	2	
83-Fr-6	58	4	2	-	36	-	
83-12-1	34	4	8	22	24	6	2 breccia
83-28-1	24	-	-	14	60	2	
83-28-1	12	4	2	8	66	8	